Final Report for Hydrogeologic Studies of the Spruce Hole Bog Sand and Gravel Formation

by

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Executive Summary

The sand and gravel formation that contains the Spruce Hole Bog was studied in order to more clearly delineate the hydrogeology of the system and the ecology of the bog. Numerous monitoring wells and one production well were installed in the formation. Ground water and surface water levels were monitored over a five-year period. In addition, precipitation and streamflows were also monitored. A pumping test was performed on the production well with attendant analyses of well water quality.

The sand and gravel formation is considered and aquifer and is capable of yielding upwards of 350,000 gallons of water per day. More realistically, one production well, centrally located in the formation, can yield approximately 300,000 gallons per day. The production well installed as part of this study is considered a test well. It is physically located in the Town of Lee. This well can be used as a water supply well, however it needs to be developed (purge fine materials away from the gravel pack around the well screen) before it can be used in this capacity. The quality of this ground water is excellent. In a water sample taken at the end of the pumping test, all tested water quality parameters were better than US EPA primary and secondary drinking water standards.

The formation can be used as a 'storage reservoir' for applied surface water (artificial recharge and subsequent recovery). In this case, water from the Lamprey or Oyster Rivers could be pumped to a recharge basin, for infiltration purposes. Depending on the location of the recharge basin, most of the pumped/infiltrated water could have a residence time in the formation of greater than one year. If the formation were not used for groundwater supply, any artificially recharged water would follow the natural groundwater flowpath to streams that discharge into the Oyster River.

The Spruce Hole Bog appears to be insulated from the groundwater below by all of the dead and decomposed peat at its base. The water level of the bog seems to have risen over time, as evidenced by core samples from the standing dead trees in and around the bog.

Recommendations for future efforts for this formation include:

1. Continue monitoring stream flows, well water levels, and bog characteristics, on at least a monthly frequency.
2. Continue the very close scrutiny of development proposals for private property on the formation. The best scenario is for the Town to own this property, in lieu of this; incentives may be necessary to convince private property owners to maintain the formation in a more or less undeveloped state.
3. Activities at the Town gravel pit in the formation should be carefully selected in order to minimize the potential for soil and groundwater contamination.
4. If artificial recharge is to be seriously considered, a field scale study should be performed in order to verify the estimates made by the computer simulations performed during this study.

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1. Introduction

In 1992, the Town of Durham and the University of New Hampshire agreed to embark upon an evaluation of the potential of the Spruce Hole Aquifer to act as a water supply. The results of this study are presented in this report. The primary objectives of the study were:

- Delineation of the aquifer,
- Determination of the safe ground water yield,
- Evaluation of water quality,
- Location of water supply well(s),
- Wellhead delineation,
- Assessment of the potential for artificial recharge,
- Determination of the baseline vegetation of the bog, and
- Establishing permanent long-term vegetation monitoring plots.

This Final Report is meant to answer some simple questions focused on the above-mentioned studies.

2. What is the Spruce Hole Bog Formation?

The southern boundary of the Spruce Hole sand and gravel formation extends to Wednesday Hill Road. To the north, the formation's surface expression ends by the time one reaches Mast Road (the formation here is covered by about 30 feet of clay, however north of Mast Road, the clay cover is absent and the sand and gravel actually continues north to Lee Five Corners). Along the west, the formation is bordered by a northerly flowing tributary to Chesley Brook. To the east, the formation has no special delineator except to follow the general control boundary of the elevation contour 100 feet above mean sea level (ft. MSL). These formation boundaries are depicted as the solid line in figure 1. The USGS (Moore, 1990) mapped this deposit, along with others in the Lamprey and Oyster River basins, and, based upon limited drilling, also identified some expected thicknesses of the ground water zones (figure 2). The thickness of the ground water zone should not be confused with the total thickness of the sand and gravel. The ground water zone is the lower portion of the sand and gravel where pore spaces are filled with water. Above this zone reside the same sands and gravels; however, they are unsaturated. The unsaturated sands and gravels are those, for example, that are currently mined. A CAD map of the study area, with elevations and well locations, may be found in Appendix 4.

3. What is the Spruce Hole Bog?

Spruce Hole Bog has been recognized as a unique ecological area by the US National Park Service and is a registered National Natural Landmark (Favour, 1971, Bayless, 1981). The Natural Landmark evaluation report states that, "Spruce Hole Bog has exceptional value in that it is an ecological community significantly illustrating the characteristics of a typical Sphagnum-Heath bog localized in a specialized geological setting, i.e., it is a true kettle-hole bog." The bog is cited as being the last of six kettle-hole bogs in southern New Hampshire; the other five bogs apparently have been destroyed by development. Dr. Albion Hodgdon collected vascular plants at Spruce Hole bog from 1930 to 1969 and his voucher specimens are contained in the Hodgdon Herbarium at the University of New Hampshire. Hodgdon's research is the only published botanical work done at Spruce Hole Bog. His species list was incomplete, but provided some information on the past extent of some vascular plant assemblages.

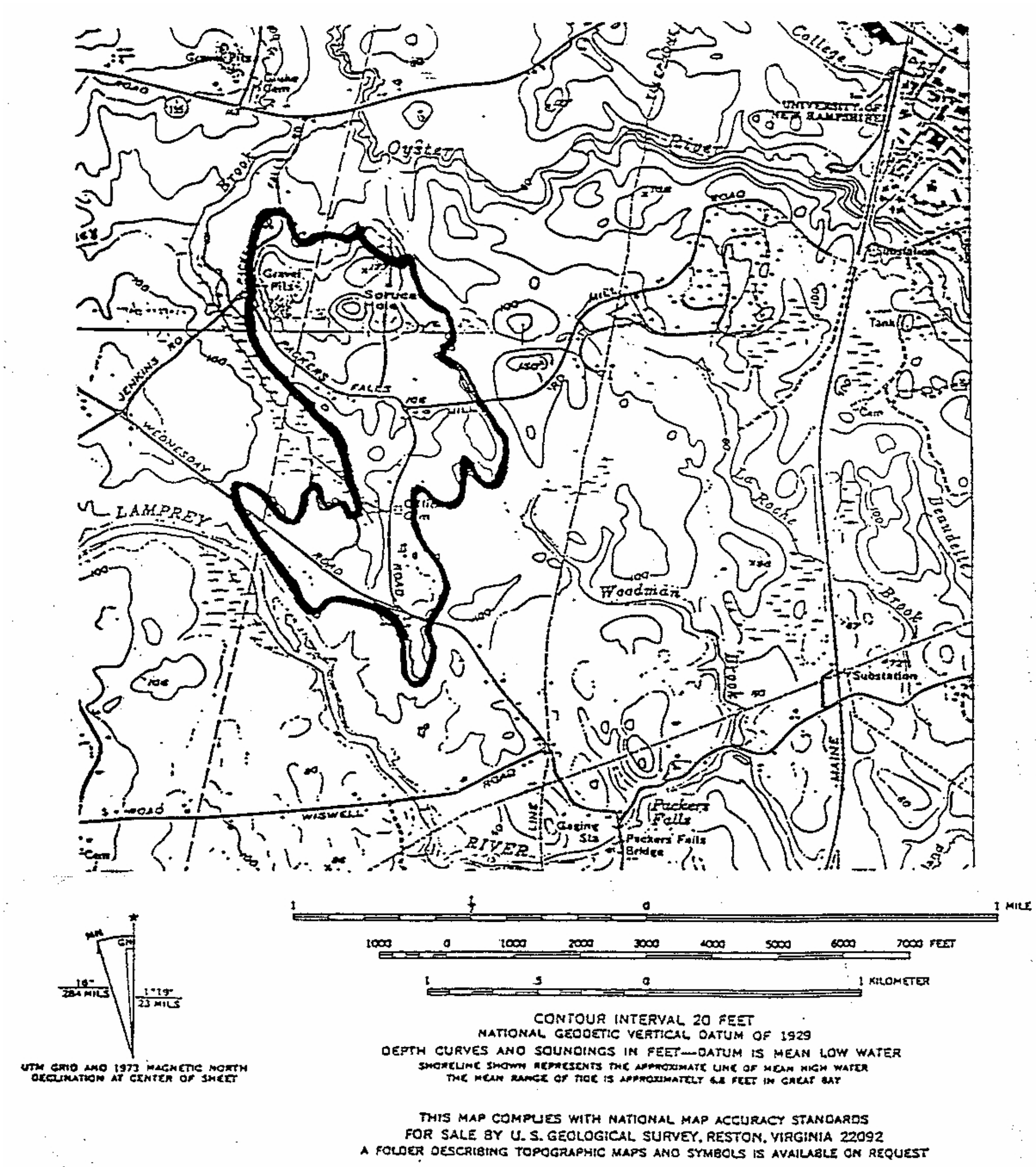

Figure 1 The Sand and Gravel of the Spruce Hole Formation

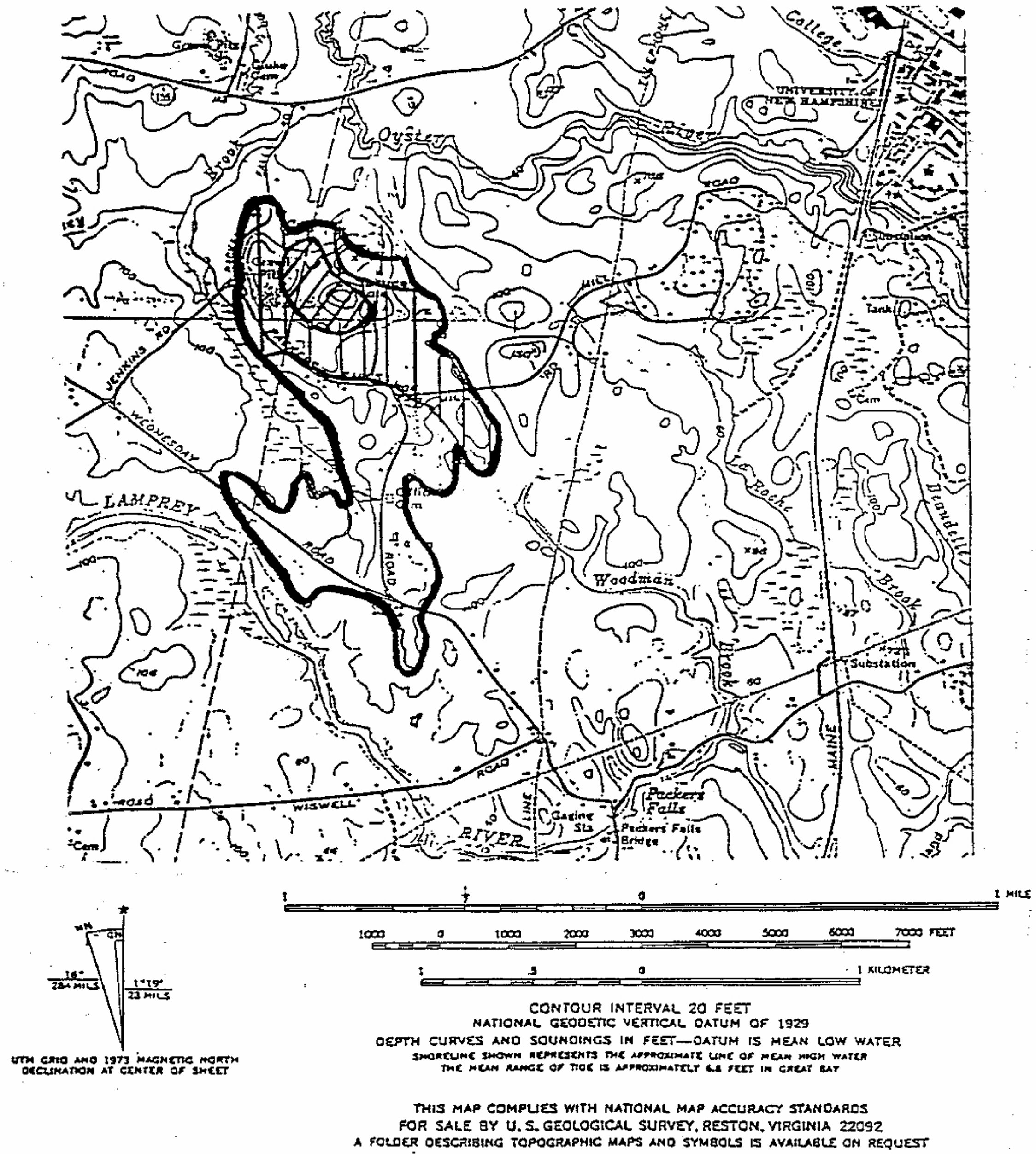

Figure 2. The Primary Aquifer Zone of the Spruce Hole Aquifer (diagonal lines indicate a saturated thickness greater than 60 feet, the vertical lines define the area with a saturated thickness greater than 20 feet), after Moore, 1990.

Spruce Hole Bog has been the site of numerous entomological studies including two Master's theses; Debboun studied mosquitoes at the bog, and Donaldson-Fortier studied mites associated with peat mosses. It is also known that the insect fauna is particularly diverse; over 1700 insects have been collected (D. Chandler, 1995). Of particular interest are the banded bog skimmer dragonfly, a species endemic to New England, and the blundering Stenus rove beetle, which is only found in Spruce Hole Bog and one other bog in Connecticut. The bog elfin butterfly, which has a specific dependence on peatland black spruce forests for its existence, has been collected historically from the bog.

4. Is the Spruce Hole Bog Formation an aquifer?

The sands and gravels of the Spruce Hole formation can easily transmit ground water. Coupling this fact with the thickness of the ground water zone (upwards of 100 feet) means that the formation can readily accept and yield water. The hydraulic characteristic that describes how easy a formation transmits water is called hydraulic conductivity and is denoted by the letter 'K'. Hydraulic conductivity has the units of velocity (length per time), for example, feet per day. The thickness of the ground water zone, known as the saturated thickness, is denoted by the letter 'b'. The hydraulic characteristic that describes the combination of the saturated thickness and the hydraulic conductivity is called the transmissivity and is denoted by the letter 'T'. T is the product of b times K. The higher the values of T, K, and b, generally the more water a formation can supply to a pumping well. The hydraulic parameter that describes the amount (volume) of water in the pore spaces is called the specific yield, and is denoted by S_y. Specific yield indicates the water available through gravity drainage of the pore spaces: this is the water obtained by pumping a well in an unconfined overburden formation such as Spruce Hole. S_y is dimensionless. T, K, and b can be estimated through indirect measures (for example by using geophysics and interpreting the data) or by direct measurements (for example drilling/installing wells then conducting a pumping test). Both methods were used for the performance of this study. Direct measurements require the use of wells. Twenty-eight monitoring wells and one test well were installed during the performance of this study, and their sizes ranged from ½-inch diameter observation wells to the 8-inch test well.

A pumping test of the test well was performed from 13 September 1994 to 21 September 1994. Data from the pumping test may be found in electronic form and tables in Appendix 5. A nearly constant pumping rate of 265,000 gpd (184 gpm) was used. For the Spruce Hole formation, the pumping test yielded the following values in the vicinity of the pumping well: $T = 5200\ ft^2/day$ and $S_y = 0.2$. These are values indicative of an aquifer. It must be stressed that these values are valid for the central region of the formation. At the fringes of the formation, the saturated thickness is less and there is more silt mixed in with the material, therefore the values of T and S_y would not reflect those of an aquifer. Thus, in the central portion (roughly 0.5 square miles in size) the Spruce Hole Bog formation is an aquifer, and as a best estimate for the limit of this formation, it is outlined by the 20 ft. saturated thickness contour found in figure 2. The formation outside of the 20 ft. saturated thickness contour zone is relatively permeable, but due to the limited saturated thickness, cannot supply well yields typically expected of community water supply wells. However, wells in such regions could produce upwards of 43,000 gallons per day (gpd), which in rural areas could meet the average daily needs of up to 600 people. This does not mean that the portion of the formation outside of the 20 ft. contour does not deserve protection. Depending upon the ultimate location and pumping rate of a production well, these cited areas might be a source of water to the production well. These would not be locations for the production well.

The Spruce Hole formation does contain an aquifer, and this aquifer is located as the land contained within the 20 ft. saturated thickness contour in figure 2.

5. How much water can the aquifer deliver to a pumping well?

Based upon the pumping test and the results of computer modeling, one pumping well centrally located in the primary aquifer can produce approximately 300,000 gallons per day (gpd). It may be possible to locate one to three other wells and capture an additional 100,000 gpd. These additional wells would no doubt reduce the yield of the centrally located, single well from 300,000 gpd; however, the additional wells would tap ground water that is relatively inaccessible to one well. Thus, one well can yield upwards of 300,000 gpd and a well field can yield up to 350,000 gpd.

6. What is the source of the ground water in the Spruce Hole Formation?

The water chemistry analyses that were performed on well water samples indicate that the primary source of this ground water is precipitation that infiltrated the land surface and escaped the demands of evaporation and transpiration. At this site, ground water is normally replenished by precipitation between November and June. There may be a small fraction of the ground water in the Spruce Hole formation that is derived from upward leakage from the underlying bedrock; however, there was not a very strong chemical signature of bedrock ground water detected in the water samples from monitoring or test wells. Likewise, there was no chemical signature of the bog water in these samples. There most likely is some bedrock water that finds its way to the sand and gravel aquifer, but the quantity is extremely small compared to the rate of water flowing through the aquifer resulting from precipitation recharge. The water table map for the formation may be found in Appendix 6. This map reinforces the precipitation recharge model.

7. Is the water potable?

During the pumping test, water samples were taken from the pumping well and analyzed for the parameters regulated in the Safe Drinking Water Act. The results showed that the ground water quality characteristics of the Spruce Hole aquifer do not exceed either the primary or secondary drinking water criteria. The water is a safe, potable water source. The results of the water quality analyses may be found in Appendix 1.

8. Where is the optimal location for a production well?

The results of the geophysical and drilling programs both indicate that the thickest portion of the formation, and the thickest location of aquifer, is in the vicinity of the 8-inch test well (see figure 2 for saturated thickness). The area of the largest saturated thickness is bounded roughly by the Spruce Hole bog to the east, the deeper excavations of the gravel pit to the north and west, and monitoring well 102 to the south.

9. Can the test well be used as a production well?

The 8-inch diameter test well had the primary purpose of hydraulically testing the aquifer. The siting, design, construction, and development of the well were based on this purpose. At the present, the well has a very poor connection to the aquifer because it was poorly developed. After a well is constructed, there are fine sediments contained in the area outside of the well screen that need to be removed. Well development purges these fine sediments, and by doing so, there is a better hydraulic connection between the well and the aquifer. Good hydraulic connections minimize the well drawdown when pumping, thereby minimizing pumping costs.

The test well can be used a production well. Before it is put on-line, the well needs to be developed, preferably by the jetting and pumping technique. The estimate for this development is $7,000. The completion specifications for all wells may be found in Appendix 2.

10. What is the natural hydraulic connection between the bog and the aquifer?

The bog has a water surface elevation that ranges between 97-100 feet above the sea level datum (ft MSL). The water depth in the bog ranges from less than an inch at the margins to over 16 feet in the central, open-water portion. The bog is a peat bog, and a characteristic of a peat bog is that organic material from the floating peat collects at the base of the water. This organic material at the base slowly decays and creates a very restrictive layer: a layer with a very low hydraulic conductivity and which, therefore, does not allow water to easily pass through it. At the margin of the bog, this restrictive layer is nearly absent. Figure 3 depicts a sketch of the bog-aquifer-restrictive layer system. Wells at the margins of the bog, in the aquifer, exhibit a water table elevation that ranges between 85-90 ft MSL. Because the water level in the bog is always higher than the water table elevation of the aquifer, water always flows from the bog to the aquifer, but to do so, it must first pass through or over the restrictive layer. At the margin of the bog below the thin restrictive layer, there is actually a zone of unsaturated sand and gravel before encountering the water table. This was verified during the installation of the 202-series wells. At the center of the bog, due to the thousands of years of its development, the restrictive layer is upwards of 20 feet thick and separates bog water from the aquifer. At this location there is no unsaturated zone between the two. Even here, the very large difference between the bog water level and the aquifer water level means that water flows from the bog to the ground water below. If the restrictive layer were not there, the bog water level would drop to that of the ground water table. It is the restrictive layer that maintains and preserves the bog in its current perched status above the aquifer, and this restrictive layer is continually growing and expanding. Thus, there is very limited hydraulic connection between the Spruce Hole bog and the aquifer below. Water slowly seeps through the restrictive layer from the bog to ground water below. During high water level periods in the bog (normally March to April), the bog can fill with water and water can then “spill over” the edge of the restrictive layer, analogous to overfilling a teacup. During this time, the ground water levels immediately next to the bog reflect this influence. Technical descriptions of the physical evidence of the bog restrictive layer may be found in Appendix 3.

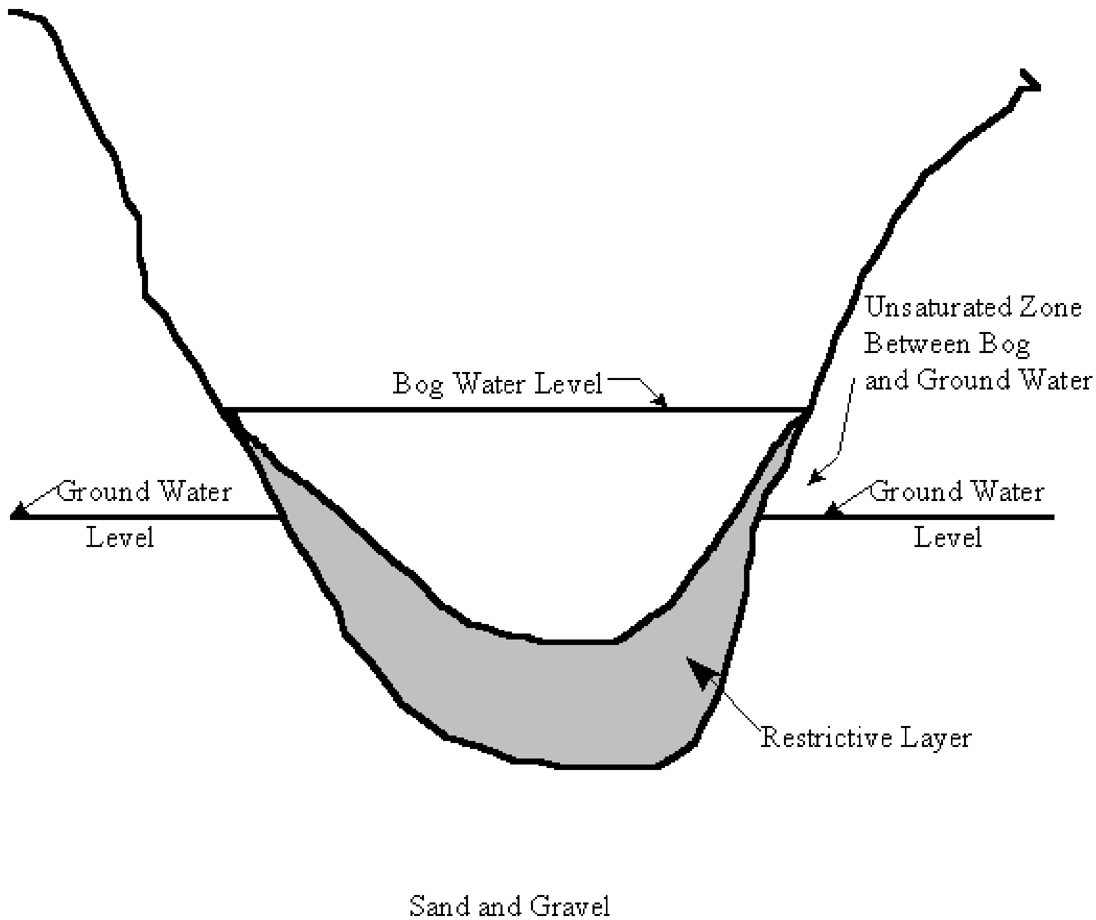

Figure 3. Sketch of bog-aquifer-restrictive layer system.

11. Is there an adverse effect on the bog from a production well in the formation?

Due to the presence of the restrictive layer between the bog and the aquifer, there is very limited hydraulic connection between the bog and the aquifer. On the margins of the bog, where there is an unsaturated zone between the bog's lower restrictive layer and the aquifer water table, there is no significant effect of ground water pumping on the leakage of water from the bog to the aquifer. This is because the unsaturated zone effectively acts as another barrier to flow besides the restrictive layer.

Below the central part of the bog, when looking at the vertical layering of materials (bog peat, then restrictive layer, then aquifer), the leakage of water from the bog to the aquifer is controlled by the difference in head (water level) between the bog and the underlying aquifer as well as the hydraulic conductivity of the restrictive layer. The natural leakage from the bog is highest when the difference between the bog water level and the aquifer water table is maximum. During a normal year, this is November to December. The time of year when leakage through the restrictive layer is minimal is May. At this writing, no direct measurement of leakage has been made; however, it is estimated (using the water level differences and the measured restrictive layer hydraulic conductivity) to be on the order of 10 gallons per day. Put in terms of how this leakage rate translates to a fall of the bog water level when there is no rainfall recharge: the bog water level would drop on the order of fractions (thousandths) of an inch per day with leakage of 10 gallons per day. A leakage rate of 10 gallons per day yields a bog water level change on the order of what is observed in the late fall every year.

For this study, ten wells were installed around and within 25 feet of the bog margin: four wells were in shallow groundwater at the edge of the restrictive layer and six wells below the restrictive layer. The deeper wells verified the existence of the unsaturated zone below the restrictive layer at the bog margin. Three of the six deeper wells were completed as a 'triplet': in very close proximity to one another, but with screens set at various depths below the ground. The triplet more accurately indicated which zones, in the vertical, send water to the pumping well. In addition, this triplet displays the natural vertical flow of ground water at the bog margin. Over the course of the pumping test, the shallow wells showed no detectable effect of the pumping on their water levels, neither did the staff gages in the bog. The deeper wells showed about 0.3 to 0.5 feet of drawdown at the margin of the bog closest to the pumping well. The bog level actually rose during the pumping test due to a cumulative rainfall amount of almost one inch during the pumping test. The triplet wells indicated that the pumping well affected the deeper zones below the bog rather than shallower zones at the bog and restrictive layer.

Overall, a pumping well for ground water supply has the ability to decrease the water level of the aquifer and this, in turn, increases the difference in water elevations between the bog and the aquifer. The increased water elevation difference technically allows more water to be forced through the restrictive layer. However, it is estimated that in a scenario of maximum pumping, the rate of water loss from the bog would be an increase of 5-10% (about ½ gallon per day). In the short run (less than three years), this would be difficult to measure. In the intermediate time (three to ten years), the bog water level may stabilize (it has a history this century of increasing) at a slightly lower level (less than one foot). In the long run (greater than ten years), the bog will reach a new equilibrium position and then continue its process of increasing the water level (due to the ever-increasing thickness of the restrictive layer) until such time that the rate of annual leakage equals the net annual precipitation recharge. Artificial recharge would negate any negative effects on the bog from pumping of a production well.

It is believed that ground water pumping will not measurably affect the water level of the Spruce Hole Bog. This belief stems from the characteristics of the impermeable layer that exists below the bog.

12. Is this water/formation of value to the town?

The Town of Durham/University of New Hampshire water supply system currently has three sources of water. The Oyster River and the Lee well are the two primary sources, and in low flow times, the Lamprey River is tapped. In a 1995 study by Nerney, the reliability of these supplies was analyzed. Although on the average, the Oyster River has more than enough water to supply the system, the variability from high flows to low flows, coupled with the variability in demand, leaves the system very dependent on the Lee well and the Lamprey River. The year 1995 revealed that even the Lamprey River can exhibit flows low enough to adversely affect water supply. If more instream storage could be created (on the Oyster or Lamprey), the system could easily make it through low flow/high demand times (typically August and September). However, there have been no proposals made on new dam locations or increased capacity added to existing dams and reservoirs, except for the possible dredging of reservoirs. At this writing, on the average, there is a one-fourth to one-third chance that the Oyster River and Lee well will not have enough water to supply the system to meet demands in any given August or September.

The Durham/UNH water system provides, on the average, one million gallons per day. The Spruce Hole Bog formation can provide a sustained 30% of the present day demand, and this water need not pass through the water treatment plant. It should be recognized that the natural outlet for Spruce Hole aquifer groundwater is to tributaries of the Oyster River. Therefore, the long term pumping of Spruce Hole ground water will result with an almost concomitant decrease in Oyster River flow (300,000 gallons per day = 0.46 cfs).

It is anticipated that the demand for water will slowly increase as the number of customers slowly increases. In lieu of increased capacity in reservoir storage, the Spruce Hole Bog formation is a very valuable resource to the Town. It should be underscored that typically ground water supplies are much cheaper to develop than surface water supplies. In this case, due to the distance between the most favorable well location and the water supply system, there will be a significant capital cost for piping and pumping in order to bring Spruce Hole ground water on line. Thus, it is reasonable to weigh this alternative against others.

13. What are management practices that should be employed to protect the Spruce Hole Bog ground water?

If the Town seriously wants to use any of the ground water from the Spruce Hole Bog formation, it must consider protective measure for the formation. The primary reason for protective measures is to avoid contamination of the formation or the ground water that would then render the ground water as unpotable unless some form of treatment were employed. The visible costs of protection measures (lost tax base, program administration, structural measures, incentives to private property owners) must be weighed against the potential costs of formation remediation and water treatment that can arise without protection. In addition, one must weigh-in the lost opportunity cost resulting with having to search for another water supply if the Spruce Hole Bog formation were to be lost. Globally, the costs of aquifer protection measures are but a fraction of remediation/treatment or lost opportunity costs. This has been illustrated time and again with water supplies. To repeat, protection must be employed if the Town desires to use the ground water now or in the future.

The best protection measure is to leave the land that overlies the formation, undeveloped and restrict access to it. This measure should be employed over the portion of the formation that will supply water to the pumping well(s). Since the final pumping well has not been situated or constructed, outside of protecting all of the area identified in figure 1, the most important area to protect is the formation that has in excess of 20 ft. of saturated thickness (as depicted in figure 2). A pumping well that is centrally located in the formation, that pumps at or near to the maximum predicted sustained yield of 300,000 gallons per day, will reach out for water past the contour of the 20-ft. saturated thickness to the small streams and wetlands that surround the bog. The ring of land contained between the 20-ft. saturated thickness contour and these surrounding water bodies also deserves protection. There do exist roads, houses, and septic systems in this ring. A significant portion of the formation that needs protection is in the Town of Lee.

Management and protection practices for the aquifer include any of the following listed tools:

- Zoning Ordinances
- Subdivision Ordinances
- Site Plan Reviews
- Design Standards
- Operating Standards
- Source Prohibitions
- Purchase of Property or Development Rights
- Tax Rate Incentives
- Public Education
- Ground Water Monitoring
- Household Hazardous Waste Collection
- Water Conservation

14. Can an artificial recharge strategy be employed at the site?

The continuation of studies over the summer and fall of 1996 was primarily directed at this question. The computer models indicated that if water, say from the Lamprey River, was used to artificially recharge the formation, there would be the added possibility of using the formation as a reservoir. If water was to be applied at the end of May or beginning of June at a location south of the bog, it would naturally flow to the west and north, toward the favorable location for a single production well. Three months later, 90% of the recharge water would still be in the formation. One year and three months later, almost half of the applied water would still be in the formation. Of the water applied in May/June and then pumped the following August/September, only 30% to 75% could be recovered, the recovery being a function of the final well(s) location(s) and pumping rate(s). In general, it takes one to four days for rainfall to move through the unsaturated zone and recharge groundwater. There does not seem to be an extensive restrictive layer as previously thought. When a prolonged dry spell occurs, it may take more than ½ inch of rain before any recharge reaches the groundwater. This is because the thick unsaturated zone requires that soil moisture needs be satisfied before infiltrated rainfall can percolate down to the groundwater. When soil moisture is high (usually April to June), very small amounts of rainfall can recharge the groundwater.

By serendipity for this study, in October of 1996 Hurricane Bob dumped nearly one foot of precipitation on Spruce Hole, most of this rainfall in just one day. Water levels were then recorded daily for the next two weeks. This data quite clearly indicates that artificial recharge is viable for the Spruce Hole formation. The water level and rainfall data for Hurricane Bob may be found electronically in Appendix 5. The annual series of well water levels (for example well MW101) always exhibit peak levels that lag in time behind that of the bog water level. The bog can react immediately to precipitation whereas ground water can only react after water has slowly percolated through the thick unsaturated zone above it.

15. Will artificial recharge adversely impact the bog?

Again, because of the restrictive layer at the base of the bog, the bog is fairly insulated from pumping or recharge stresses in the aquifer. Artificial recharge would tend to increase the ground water levels in the aquifer below the bog. This, in turn, would tend to reduce the rate of leakage through the bog restrictive layer, which, would tend to maintain bog water levels higher than a natural condition. The bog has a natural high water level control. At high bog water levels, bog water flows out the margins and percolates down to ground water. Much of the magnitude of the change presented here would be difficult to measure since it would be so small. The absolute magnitude would be related to the amount of water recharged, the location of the recharge basin, the location of the pumping well, and the well pumping rate. It would be possible to continually pump from the formation and periodically artificially recharge it so that there would be no net change in water levels below the bog. Since the bog is dynamic and its water level is naturally increasing slowly with time, it will require intensive study to clearly delineate and separate the natural bog hydrology from those induced by pumping/recharge, since both of these processes will be very subtle at the bog location.

16. What is so special about the bog?

Thirty-seven vascular plant species were found in the bog during the present study. One orchid species, grass pink, which was reported by Hodgdon in 1969, was not seen in the bog over the three years of field study conducted for this study. Even with grass pink included as part of the Spruce Hole flora, vascular plant species richness at Spruce Hole was much lower than that reported for other New Hampshire peatlands. Richness at these other sites ranged from 70-124 species. Two Spruce Hole species, grass pink (assuming it remains extant) and pitcher plant, are uncommon in New Hampshire and are formally listed as species of ‘special concern’ in the state. Grass pink may have been lost from the bog within the past 27 years.

Sixteen moss and liverwort (bryophyte) species were found at Spruce Hole, resulting in a total plant species richness of 53. Spruce Hole Bog is the only peatland known in New

Hampshire for which a complete bryophyte flora exists. The relative bryophyte richness compared to other peatlands is not known.

The Spruce Hole Bog classification program identified five plant communities in the bog. These were: (1) the bog forest community, dominated by black spruce, highbush blueberry, and a rich moss and liverwort flora; (2) the tall shrub community, dominated by highbush blueberry and peat mosses; (3) the low shrub community, dominated by leatherleaf, water willow, and peat mosses; (4) the peat moss-sedge lawn, dominated by cottongrass, leatherleaf and peat mosses; and (5) the "lagg" or "moat" community, dominated by cottongrass, water willow, and a unique peat moss, and which encircled the other communities, forming a border with the surrounding upland. All of these, except for the bog forest, were similar to communities reported from other New Hampshire peatlands. The bog forest appeared to be uncommon compared to other southern New Hampshire peatlands because of its dense, closed canopy of black spruce and rich understory moss flora growing on slightly raised, coniferous peat. These characteristics are more common to the bog forests of raised peatlands in northern New England, and though the flora of this community is similar to other, more northern peatlands, the assemblage itself appears to be unique for its latitude.

Many Spruce Hole plant species and most of the communities were indicative of very nutrient-poor, acidic conditions. Indeed, mean pH values in all communities except the lagg (moat) were lower than 4.0.

Considering basin morphology, floristic and community data, as well as pH values, it is clear that Spruce Hole Bog is a 'primary' or 'level' peatland, more uniformly nutrient-poor than other New Hampshire peatlands studied to date. Its basin morphology (kettle hole) and vegetation make it unique among southern New Hampshire peatlands.

17. How has the vegetation changed in the recent past, and what are the implications of these changes for management?

Mapping of living and dead white pine stems revealed that the distribution of this species on the open peat had contracted greatly over the past 40 years, from a forest of large trees [10-35 cm (4-14 inches) in diameter] that nearly encircled the pond in the center, to two small areas of regeneration in which plants did not exceed two meters (six feet) in height and appeared unhealthy. It was clear that massive mortality of the large trees on the bog mat as well as other white pines around the bog margin had occurred in recent decades. Cross dating of tree rings from increment cores and cut wedges revealed that the white pine mortality occurred in two pulses. The pines on the open peat died between 1945 and 1962, while trees around the margin died between 1985 and 1995. Dead trees, whether on the peat or rooted in till at the bog margin, had their butts covered with bog water at the time of mapping (summer, 1995). The black spruce community also appeared to have contracted based on Dr. Hodgdon's written observations and the presence of dead trees around the pond in the center of the bog. Taken together, these observations suggest a slow rise in the water level of Spruce Hole bog over the past half-century. The exact cause of the water level rise is unknown. It is apparent, however, that the plant populations at Spruce Hole are sensitive to water levels.

Should the water table continue to rise, naturally or induced by human activity, changes in plant communities and flora can be expected.

18. Acknowledgments

The primary support for this study was provided by the Town of Durham and the University of New Hampshire. In addition, the US Army Cold Regions Research and Engineering Laboratory supported the installation of the small diameter wells. Dr. Frank S. Birch and Ms. Ruth Kerwin, of the UNH Earth Sciences Department performed the geophysical work at the site and provided the first detailed geological models of the aquifer. Mr. Rob Flynn transferred all field information into GIS layers and performed all of the computer simulations. Scott Miller performed much of the floristic fieldwork on the bog. Matt Wolf performed further geophysical studies. Dr. Larry Brannaka was very helpful in the field monitoring and electronic data collection portions of this project, Dan Caouette, Holly Gallagher, Matt Jennings, Scott Nerney, Ellen Douglas, Jon Ordway, Peter Merrow, Tracey Brannaka, Trisha Ballestero, Joel Ballestero, Heather Ballestero, Jeff Gray, Matt Szydlo, Rob Meyer, Carrie Novotny, Kevin Stetson, and Jeff Langlois all helped in the various aspects of field work, data collection, and data synthesis. The authors gratefully acknowledge all of these efforts.

19. List of the Masters Theses completed in association with this project (all available at the UNH Library)

Flynn, Robert H. September, 1996, A Three-Dimensional Ground Water Model of the Spruce Hole Aquifer in Durham, NH, Department of Civil Engineering.

Kerwin, Ruth, May 1993, A Detailed Seismic Refraction Survey of and a Ground Water Model for the Spruce Hole Aquifer, Durham, NH, Department of Earth Sciences.

Miller, Scott D., 1996, The Vegetation and Tree Ring History of Spruce Hole Bog, Department of Plant Biology.

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Appendix 1.

Water Quality Analyses for the Test Well

The following pages contain the analytical results of a water sample taken at the end of the pumping test, before the pump was shut down. Samples were kept in NH DES supplied bottles, and the bottles kept on ice in a cooler. They were brought to the NH DES lab, eight hours later where they were analyzed for all drinking water parameters. The samples were taken at the end of the seven day pumping test from a bleeder tap off the main discharge line.

State of New Hampshire
DEPARTMENT OF ENVIRONMENTAL SERVICES
Water Supply Report

Reporting and Billing Address

SPECIALS FOR WATER SUPPLY

Sample Location

System ID : 999999999 - SPECIALS FOR WATER SUPPLY
Owners Name: RESEARCH PROJECT SPRUCE HOLE
System Name: SPECIALS FOR WATER SUPPLY
City or Town:

Additional Information

Sample No.: 283442
Person Sampling: DR THOMAS BALLESTERO
Date sampled: 09-20-94, 18:25
Date Received: 09-21-94, 09:20
Date Completed: 11-15-94
Person Receiving: TJC
Raw/Treated/Unk.: RAW
Sample Month, Yr.: Nov., 1994
W.S. Category : SDWA / Specials / Other

Comments:

SAMPLES TAKEN AT 8" GRAVEL PACKED WELL IN LEE OFF PACKERS FALL RD
SOC'S BY EPA METHODS:504,505,506,531.1,547,550.1,555
VOC'S BY EPA METHOD: 524.2

Langlier Index, Ph = 7.20 = -2.3090

Test Name			Result (see units)	FRD ID #	Standards Allowable
Total Alpha Screen	pCi/L	<	1.0000	0000	
Uranium	pCi/L		Deleted	4006	
Radium 226	pCi/L		Deleted	4020	< 5
Radon gas	pCi/L		1800.0000	4004	
Adjusted Gross Alpha	pCi/L		Deleted	0000	< 15
Beryllium	mg/L	<	.0010	1075	< .004
Arsenic	mg/L	<	.0050	1005	< 0.05
Barium	mg/L	<	.1000	1010	< 2.0
Cadmium	mg/L	<	.0010	1015	< .005
Chromium	mg/L	<	.0100	1020	< 0.10
Copper	mg/L	<	.0500	1022	< 1.3
Iron	mg/L	<	.0500	1028	< 0.30
Lead	mg/L	<	.0050	1030	< .015
Mercury	mg/L	<	.0010	1035	< .002
Nickel	mg/L	<	.0200	1036	< 0.10
Selenium	mg/L	<	.0050	1045	< 0.05

Silver	mg/L	<	.0100	1050	< 0.10
Sodium	mg/L		3.1400	1052	< 250
Thallium	mg/L	<	.0010	1085	< .002
Zinc	mg/L	<	.0500	1095	< 5.0
Alkalinity (CaCO3)	mg/L		23.2000	1067	
Chloride	mg/L		2.0000	1017	< 250
Fluoride	mg/L	<	.1000	1025	4.0
Total Hardness (CaCO3)	mg/L		21.2000	1915	
pH	Units		7.2000	1925	
Specific Conductance	uMHOs		62.0000	1064	
Sulfate	mg/L		2.0000	1055	
Turbidity	NTU	<	1.0000	0100	
Cyanide	mg/L	<	.0400	1024	< 0.20
Manganese	mg/L	<	.0100	1032	
Methane, dichloro-	ppb		Below Detection	2964	
Methane, dichlorobromo-	ppb		Below Detection	2943	
Methane, tribromo-	ppb		Below Detection	2942	
Methane, trichloro-	ppb		Below Detection	2941	
Methane, tetrachloro-	ppb		Below Detection	2982	
Methane, chlorodibromo-	ppb		Below Detection	2944	
Ethane, chloro-	ppb		Below Detection	2216	
Ethane, 1,1 dichloro	ppb		Below Detection	2978	
Ethane, 1,2 dichloro	ppb		Below Detection	2980	
Ethane, 1,1,1trichloro	ppb		Below Detection	2981	
Ethane, 1,1,2trichloro	ppb		Below Detection	2985	
Ethane, tetrachloro(1122)	ppb		Below Detection	2988	
Ethylene, 1,1 dichloro	ppb		Below Detection	2977	
Ethylene, trichloro	ppb		Below Detection	2984	
Ethylene, tetrachloro	ppb		Below Detection	2987	
Propane, 1,2 dichloro	ppb		Below Detection	2983	
Benzene	ppb		Below Detection	2990	
Benzene, chloro	ppb		Below Detection	2989	
Benzene(s), dichloro	ppb		Below Detection	2401	
Benzene, ethyl	ppb		Below Detection	2992	
Toluene	ppb		Below Detection	2991	
Ethylene, chloro	ppb		Below Detection	2976	
Methane, bromo	ppb		Below Detection	2214	
Methane, chloro	ppb		Below Detection	2210	
Methane, trichlorofluoro	ppb		Below Detection	2218	
Aldrin	ppb		Below Detection	2356	
Dieldrin	ppb		Below Detection	2070	
Endrin	ppb		Below Detection	2005	
Heptachlor	ppb		Below Detection	2065	
Heptachlor epoxide	ppb		Below Detection	2067	
Toxaphene	ppb		Below Detection	2020	
Ether, 2chloroethylvinyl	ppb		Deleted	0000	
Benzene,1,2,4trichloro	ppb		Below Detection	2378	
Benzene, hexachloro	ppb		Below Detection	2274	
Phthalate, dimethyl	ppb		Below Detection	0000	
Phthalate, diethyl	ppb		Below Detection	0000	
Phthalate, di-n-octyl	ppb		Below Detection	0000	
Phthalate,bis-2-ethylhexy	ppb		Below Detection	2039	
Benzo (a) pyrene	ppb		Below Detection	2306	
Styrene	ppb		Below Detection	2996	
Ether, methyl t-butyl	ppb		Below Detection	2251	
Phthalate, di-n-butyl	ppb		Below Detection	0000	
Antimony	mg/L	<	.0020	1074	< .006
hexachlorocyclopentadiene	ppb		Below Detection	2042	
Total Xylenes (o+m+p)	ppb		Below Detection	2955	
1,2dibromo3chloropropane	ppb		Below Detection	2931	

Phenol, pentachloro-	ppb	Below Detection	2326	
Calcium Hardness	mg/L	17.6000	0000	
Acetone	ppb	Below Detection	2243	
Tetrahydrofuran	ppb	Below Detection	2263	
Ether, diethyl	ppb	Below Detection	0000	
Ketone, methyl ethyl	ppb	Below Detection	2247	
Ketone, isobutyl methyl	ppb	Below Detection	2249	
Ethylene, 1,2dichloro(ct)	ppb	Below Detection	2380	
Cyclohexane	ppb	Below Detection	0000	
Carbon Disulfide	ppb	Deleted	0000	
2-hexanone	ppb	Deleted	0000	
Vinyl acetate	ppb	Deleted	2447	
Propene, 1,3 dichloro-c	ppb	Below Detection	2413	
Propene, 1,3 dichlor-tr	ppb	Below Detection.	2413	
Nitrate-N	mg/L	< .5000	1040	< 10.0
Nitrite-N	mg/L	< .5000	1041	< 1.0
Coliform, Total	(P-A)/100 ml	Absent	3100	Absent
E. Coli,	(P-A)/100 ml	Absent	3100	Absent
Carbaryl	ppb	Below Detection	2021	
Chlordane	ppb	Below Detection	2959	
Lindane	ppb	Below Detection	2010	
Methoxychlor	ppb	Below Detection	2015	
Methomyl	ppb	Below Detection	2022	
Carbofuran	ppb	Below Detection	2046	
Alachlor	ppb	Below Detection	2051	
2,4-D	ppb	Below Detection	2105	
Dicamba	ppb	Below Detection	2440	
Glyphosate	ppb	Below Detection	2034	
Metolachlor	ppb	Below Detection	2045	
Picloram	ppb	Below Detection	2040	
Silvex	ppb	Below Detection	2110	
Ethylene dibromide(EDB)	ppb	Below Detection	2946	
Dinoseb	ppb	Below Detection	2041	
Aldicarb	ppb	Below Detection	2047	
Oxamyl	ppb	Below Detection	2036	
Atrazine	ppb	Below Detection	2050	
Simazine	ppb	Below Detection	2037	
Aldicarb Sulfoxide	ppb	Below Detection	2043	
Aldicarb Sulfone	ppb	Below Detection	2044	
Di(2-ethylhexyl)adipate	ppb	Below Detection	2035	
Butachlor	ppb	Below Detection	2076	
3-Hydroxycarbofuran	ppb	Below Detection	2066	
Metribuzin	ppb	Below Detection	2595	
Propachlor	ppb	Below Detection	2077	

cts/100ml	= Counts per 100 ml	@@	= Monitoring may be needed
CN	= Confluent	>=	= Greater than or equal
>	= Greater than	<=	= Less than or equal
<	= Less than	ug/k	= micrograms/kilogram

Messages: REMINDER THE LAB WILL BE CLOSED NOVEMBER 11TH, 24TH AND 25TH
PLEASE KEEP THIS IN MIND WHEN SUBMITTING SAMPLES FOR THE MONTH OF NOVEMBER.

-

Appendix 2.

Well Completion Specifications

The next page contains the horizontal and vertical coordinates for each well, as well as the screen diameter, screen length, and screen elevation. The table also lists the radial distance of each well to the test well. Bog staff gages are also described in the table.

Well Details

Well ID	Elevation Top of Casing (ft MSL)	Elevation of Screen Interval (ft MSL)	Northing (ft)	Easting (ft)	Distance to Pumping Well (ft)	Depth of Boring (ft below grade)
Pumping Well	123.357	23.9 to -16.1	229227.1851	1170055.3378	0.00	143
2-inch Diameter wells						
101	146.469	16.5 - 6.5	229144.5538	1170264.2223	224.63	154
102	144.069	61.1 - 51.1	228882.2120	1170366.2089	464.37	93
103	138.900	58.9 - 48.9	228775.4230	1170767.5448	843.40	132
104	124.138	85.1 - 80.1	228183.7908	1170849.8557	1311.46	51
105	132.683	73.7 - 63.7	229112.7102	1171423.2184	1372.66	76
106	125.655	80.7 - 70.7	228500.0682	1171423.5075	1549.38	78
107	102.072	86.1 - 76.1	227475.2484	1172051.3221	2655.79	39
108	74.865	18.9 - 8.9	231523.1955	1170091.4546	2296.29	87
1	103.164		228988.9769	1170686.6739	674.78	
2	102.587		229206.3260	1170728.0569	673.04	
3	103.278		229145.3800	1170949.6030	898.00	
*4	102.808		228899.6362	1171001.6751	1001.42	
Small Diameter Wells						
202 M	103.991	62.5 - 72.5	229130.3989	1170608.9416	562.00	50
202 D	104.784	34.1 - 24.1	229130.7566	1170608.1964	561.21	84
202 S	104.037	94.0 - 84.0	229131.4233	1170606.8518	559.77	20
204	145.735	51.7 - 41.7	229116.4418	1170382.7411	345.63	103
205	125.966	95.0 - 85.0	228796.5059	1169593.0321	631.83	42
206 A	106.441	72.2 - 62.2	229286.1665	1169393.5460	664.41	44
207	122.873	42.7 - 32.7	229215.2805	1170052.5020	12.24	91
208	123.826	43.6 - 33.6	229198.2885	1170044.9529	30.71	91
209	96.098	65.1 - 55.1	229761.3658	1170066.7639	534.31	41
210	98.504	67.5 - 57.5	229693.4909	1170382.0293	569.36	41
1 A	103.180		228990.4470	1170685.6283	673.28	
2 A	103.777		229209.5881	1170723.2788	668.17	
3 A	102.174		229417.6138	1170948.5228	913.26	
Bog Staff Gages						
A	100.058		229009.9829	1170682.4857	663.70	
B	101.728		229044.8037	1171084.1858	1044.89	

* Well 4 was removed in 1995

Appendix 3.

Technical Discussion of the Bog Restrictive Layer

The following pages contain the technical basis for concluding that there is a hydraulically restrictive layer below the bog.

Using Water Level Data from the 202-series Wells

1. The ambient ground water gradients indicate that flow naturally moves from the top (202S) of the formation to the bottom (202D). This is most likely a direct result of leakage from the bog at its margins. The downward vertical gradient is largest when the bog water elevation is the highest. During the pumping test, ground water at the edge of the bog flowed upwards from the bottom of the formation (202D) and downwards from the top of the formation (202S) towards the middle (202M). Since the pumping well screen sits below 202D, the fact that 202M was receiving water from above and below may indicate that this region of the formation is the most permeable, and delivers the water to the pumping well. If water was being pumped from the bog by the pumping well, all gradients should have been downward.

Using the Well 202 Data and the Bog Water Level Data

2. The bog water level slightly rises in the first day of the pumping test (remnant from previous rainfall) then holds steady until the fifth day of pumping. Other wells (notably 103) farther from the pumping well than the bog as well as the 202 wells, display drawdown by 5000 minutes. Therefore if the pumping well was dewatering the bog, the bog water level should have started dropping on the third day of pumping. In addition, if the pumping well was taking water from the bog, the drawdown in nearby wells should have stabilized, and they did not.

3. Prior to any pumping, it can be seen that the bog water level sits 14 feet or higher than the adjacent groundwater represented by the 202-series wells. For the aquifer transmissivity of 5,200 ft^2/day, the aquifer hydraulic conductivity is about 75 ft/day. Given the vertical gradient between the bog water level and the 202-series wells, Darcy's law predicts that the bog would be dry in less than one day unless there was an impervious layer below it to preserve the difference in water levels or there was a continuous source of recharge (which there is not). Given that the bog water level remained constant for the first five days of pumping, there must be an impermeable layer between the bog and the formation below.

4. The bog water level reaches its annual peak and annual minimum ahead of those, respectively, of the 202-series wells. This is somewhat indicative of a cause-effect relationship in which the nearby aquifer wells respond to increased leakage from the bog every year.

Using the 202-Series Well Data and Data from Other Wells

5. For the pumping test, the well 202-series data is similar in shape to the response of wells 102 and 103 (which bracket the radial distance of the 202-series wells to the pumping well). This is important because if the bog were supplying water to the aquifer below, the 202-series well water level data would exhibit a plateau, which it does not.

Using Data from Other Wells

6. The ambient ground water piezometric map (Appendix 6) is the biggest clue that the bog is hydraulically separated from the aquifer. If there was a hydraulic connection between the bog and the underlying aquifer, there would be a mound in the piezometric map at the bog, and water would flow from this mound radially away to other locations in the formation. Such a mound does not appear in the piezometric map (there is a mound and groundwater divide near to well 104).

Well Head Protection, Recharge, Continuity

7. Since this is an unconfined formation, precipitation supplies groundwater recharge. This region experiences 44 inches per year in precipitation of which half goes to recharge on sand and gravel areas. Therefore, the land area needed to sustain 184 gpm is almost 170 acres! This is a circle around the pumping well with a radius of 1500 feet. Wells 105 and 106 did exhibit about 0.1 feet of drawdown during the pumping test. If the bog were a source of water to the pumping well, wells 105 and 106 should not have seen any measurable drawdown.

Slug Test of the Restrictive Layer

8. In the winter of 1999 (March 18) when the bog surface was frozen, a small diameter well was installed through the ice and peat. The well had a 3-ft. section of well screen. 10-ft. sections of solid pipe (riser) were then crimped onto the well screen, and the well screen driven deeper. After every 10-ft. section of pipe (riser) was added and the well screen driven further, air slug permeability tests were performed. The total well depth was 40 feet. Data from the well screen located 30 to 40 feet below the bog surface may be found in the following two figures. Analysis of the data indicates a hydraulic conductivity of 4×10^{-5} ft./day. This hydraulic conductivity is over six orders of magnitude smaller than the hydraulic conductivity of the sand and gravel below (75 ft/day). A decrease in the ground water level below the bog (for example, due to pumping) on the order of twice what was observed during the pumping test would result with an additional loss of bog surface water to ground water of about 0.5 gallons per day.

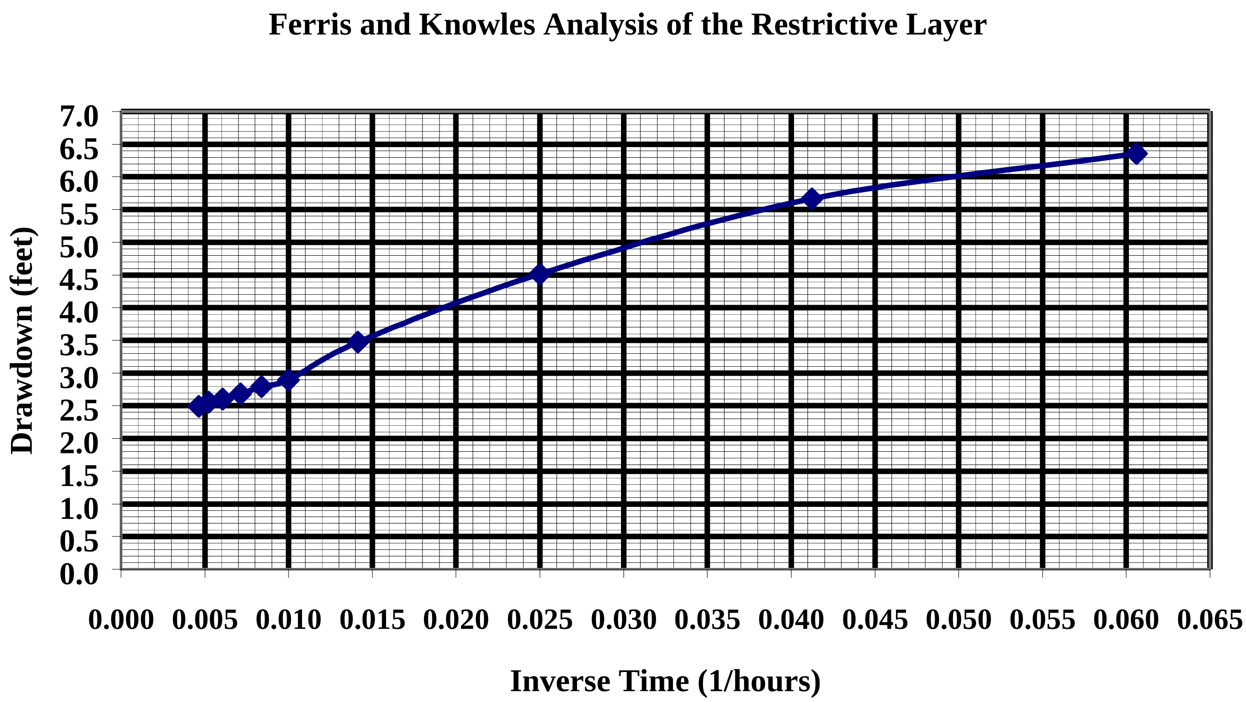

Figure 3-1

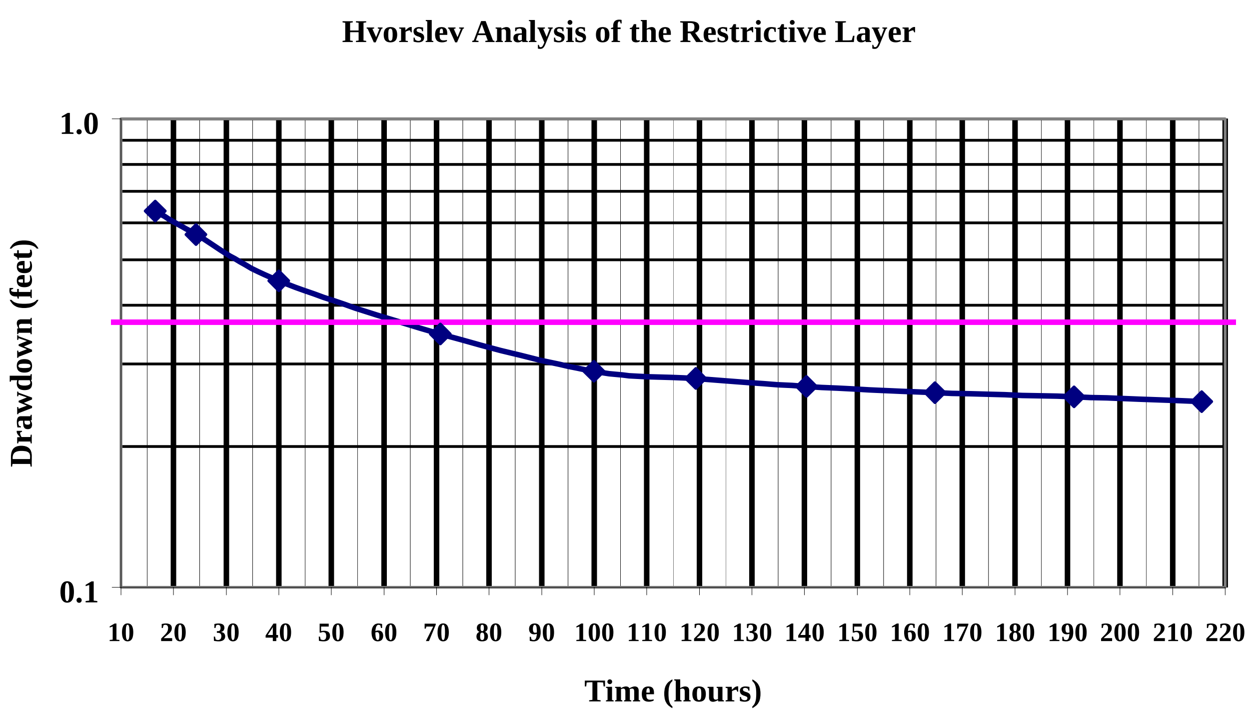

Figure 3-2.

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Appendix 4

CAD Map of the Study Area

In the following pocket-page is a color topographic map of the Spruce Hole formation. This map was saved as an AutoCAD file entitled, SPRUCE.DWG and a diskette with this file is also included in the pocket page. Included on the map are the wells and staff gages used for this study. Coordinate details of the wells may be found on the table in Appendix 2.

Appendix 5.

Ground Water and Surface Water Monitoring Data

Figure 5-1 displays the long-term water level in well 101 and the Spruce Hole Bog. All field data for water level measurements, water level elevations, staff gage readings, surface water elevations, and precipitation may be found in electronic form (in EXCEL format) on the enclosed diskette in a file entitled LONG TERM OBSERVATIONS.XLS. Also in this file is one sheet with the system response to Hurricane Bob in the fall of 1996. Figure 5-2 displays the effects that the hurricane bob precipitation had on bog and ground water levels.

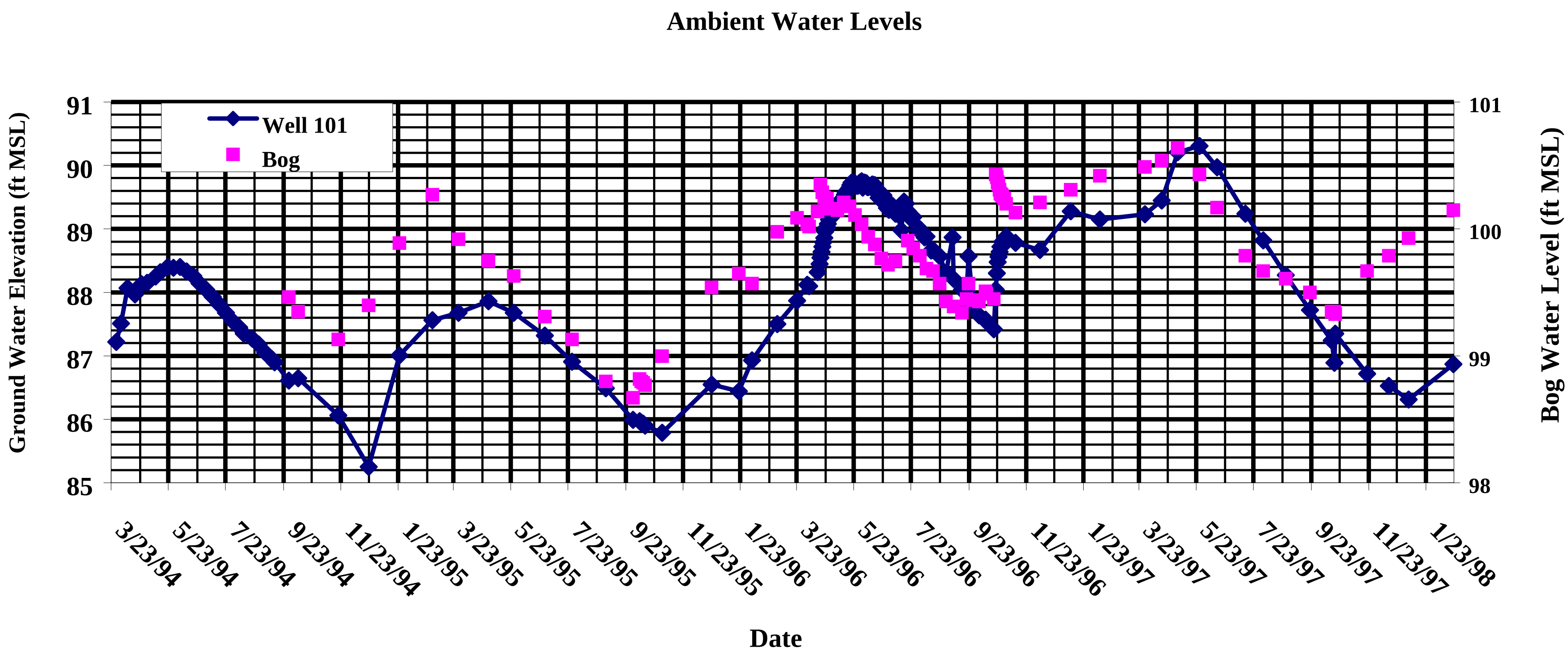

Figure 5-1. Ambient Water Elevations in the Spruce Hole Bog and Nearby Ground Water.

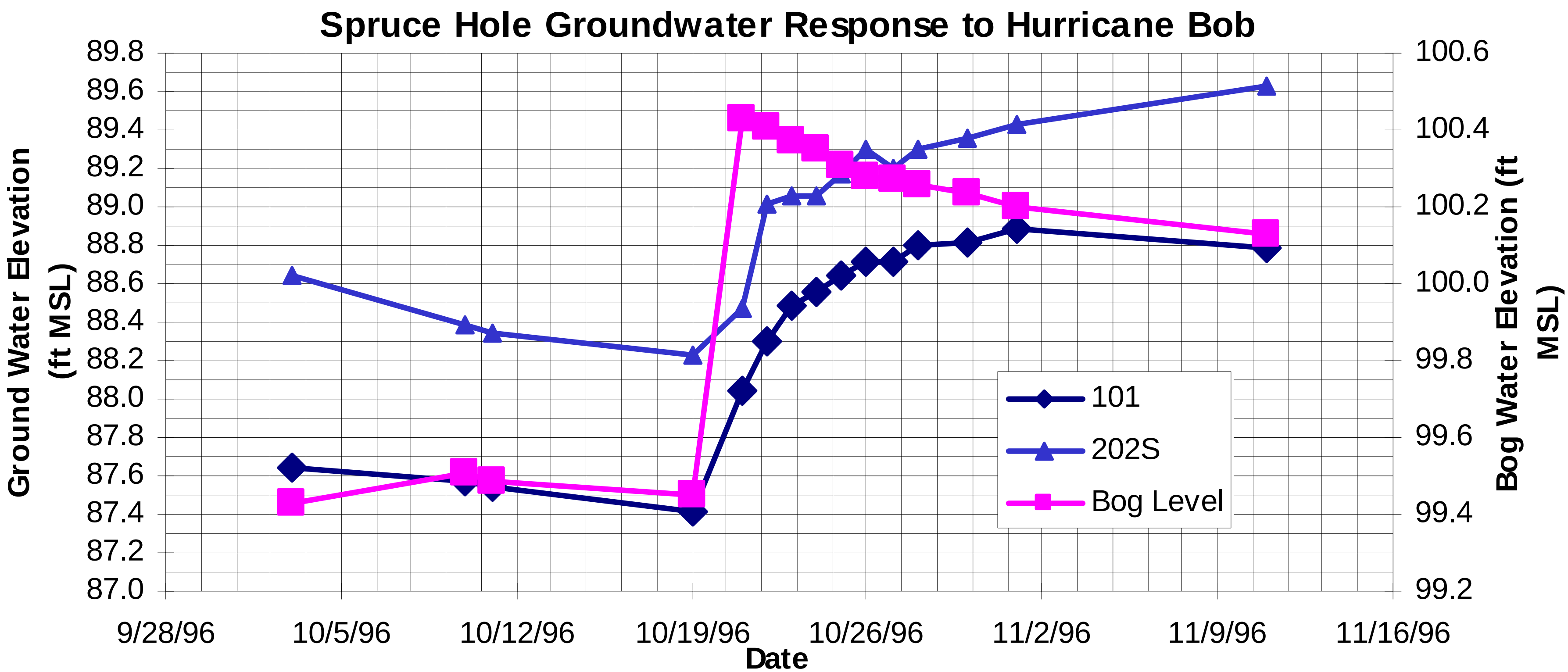

Figure 5-2. Effect of Hurricane Bob.

Appendix 6

Piezometric Head (Water Table) Map for the Spruce Hole Bog Formation

In the following pocket page, the water level data from 14 June 1997 were plotted for each well on the AutoCAD site map and then the ground water elevations contoured about these data points. The piezometric map changes in response to the weather and the season, however it preserves a general consistency in the flow directions it reveals. Ground water flow is normal (perpendicular) to the ground water contours. In general, the vast majority of water that infiltrates into the Spruce Hole formation flows northward to the Oyster River directly or indirectly (by flowing into tributaries of the Oyster River).

Appendix 7. Grain Size Analyses From Well Samples

The drilling for the 100-series wells included taking split spoon samples at various intervals. These samples were subsequently sieved for their size distribution using ASTM standards and techniques. The size distributions (per cent passing) for each sample (listed by well number, sample number, and depth interval below the ground surface) may be found in the following tables.

Well #	MW 101	MW-101	MW-101	MW-101	MW-101	MW-101	MW-101	MW-101	MW-101	MW-101
Sample #	S-1	S-2	S-3	S-4	S-5	S-6	S-7	S-8	S-9	S-11
Depth Interval (ft)	-	-	-	-	-	-	29 - 31	34 - 36	39 - 41	49 - 51
Diameter (mm)										
4.75	97.60	96.90	99.50	99.97	99.23	99.90	83.91	99.04	99.97	100.00
2	92.24	93.61	98.37	99.93	98.87	99.79	82.83	98.49	99.59	99.54
0.85	72.45	84.03	94.18	99.38	98.10	99.69	81.87	96.40	95.42	93.94
0.425	35.81	59.72	77.63	92.80	94.60	98.12	77.63	69.76	69.66	71.74
0.15	15.18	16.27	22.03	16.42	25.03	17.38	18.38	7.46	11.47	10.18
0.105	13.70	13.74	14.46	12.41	14.08	13.44	9.72	5.88	7.20	6.03
0.075	12.10	10.18	10.86	7.07	8.87	7.98	5.95	4.11	5.05	4.15

Well #	MW 101	MW-101	MW-101	MW-101	MW-101	MW-101	MW-101	MW-101	MW-101	MW-101
Sample #	S-12	S-13	S-14	S-15	S-16	S-17	S-19	S-20	S-21	S-22
Depth Interval (ft)	54 - 56	59 - 61	64 - 66	69 - 71	74 - 76	79 - 81	89 - 91	94 - 96	99 - 101	104 - 106
Diameter (mm)										
4.75	100.00	100.00	99.74	100.00	99.97	99.90	99.91	99.91	100.00	97.75
2	99.90	99.72	99.29	100.00	99.08	99.56	99.76	99.86	99.74	89.73
0.85	98.04	96.56	96.38	99.79	88.78	98.23	98.97	99.58	94.24	70.77
0.425	91.29	79.75	83.68	98.50	70.42	94.69	94.67	98.69	76.42	49.47

-

0.15	19.52	15.71	7.10	40.83	14.78	56.48	21.70	42.06	11.73	17.61
0.105	15.61	8.30	5.21	27.30	11.50	32.96	18.58	29.41	9.41	10.56
0.075	8.99	4.45	3.18	14.12	7.09	15.02	12.89	21.45	6.53	6.45

Well # Sample # Depth Interval (ft)	**MW 101 S-23 109 - 111**	**MW-101 S-24 114 - 116**	**MW-101 S-25 119 - 121**	**MW-101 S-27 129 - 131**	**MW-101 S-28 134 - 136**	**MW-101 S-29 139 - 141**	**MW-101 S-30 142**
Diameter (mm)							
4.75	99.87	99.61	98.57	99.79	95.22	96.99	96.85
2	99.64	98.52	90.00	98.63	84.58	84.36	89.15
0.85	96.05	95.00	67.44	92.20	62.25	53.32	59.91
0.425	83.83	82.65	40.94	64.59	42.95	30.38	30.73
0.15	39.30	25.18	12.10	8.58	14.62	13.05	11.06
0.105	24.04	13.38	7.92	6.38	11.70	9.86	9.28
0.075	11.07	7.06	4.77	4.10	8.99	7.41	7.02

Well # Sample # Depth Interval (ft)	**MW-102 S-1 0 - 2**	**MW-102 S-2 4 - 6**	**MW-102 S-3 9 - 11**	**MW-102 S-4 14 - 16**	**MW-102 S-5 19 - 21**	**MW-102 S-6 24 - 26**	**MW-102 S-7 29 - 31**	**MW-102 S-8 34 - 36**	**MW-102 S-9 39 - 41**	**MW-102 S-10 44 - 46**
Diameter (mm)										
4.75	96.77	95.58	77.59	73.20	99.02	99.93	100.00	97.28	100.00	99.79

2	89.75	90.78	60.46	53.64	98.35	99.63	99.61	95.73	99.50	99.15
0.85	71.81	73.60	48.01	28.98	96.57	99.16	97.70	92.39	97.77	96.45
0.425	41.34	42.58	40.65	18.69	88.24	98.61	84.86	88.06	91.34	90.26
0.15	17.61	22.08	32.50	10.20	17.86	65.36	19.55	36.32	15.35	29.64
0.105	15.90	17.77	30.83	8.21	13.05	40.92	13.89	22.69	9.03	22.15
0.075	13.81	15.19	28.29	7.06	7.93	20.53	8.26	12.64	8.91	12.08

Well #	**MW-102**	**MW-102**	**MW-102**	**MW-102**	**MW-102**	**MW-102**	**MW-102**
Sample #	**S-11**	**S-13**	**S-14**	**S-15**	**S-16**	**S-17**	**S-18**
Depth Interval (ft)	**49 - 51**	**59 - 61**	**64 - 66**	**69 - 71**	**75 - 77**	**80 - 82**	**85 - 87**
Diameter (mm)							
4.75	99.94	84.75	100.00	100.00	100.00	100.00	99.96
2	99.57	78.98	99.89	99.46	99.92	99.46	99.96
0.85	97.51	71.60	99.47	98.45	99.40	96.78	99.87
0.425	90.43	59.73	97.93	96.40	96.32	91.74	99.00
0.15	29.13	22.88	44.70	37.08	43.02	25.94	31.46
0.105	18.62	18.88	23.97	27.21	31.23	17.21	22.19
0.075	11.28	13.96	13.10	13.74	16.52	7.54	15.19

Well #	**MW-103**	**MW-103**	**MW-103**	**MW-103**	**MW-103**	**MW-103**	**MW-103**	**MW-103**	**MW-103**	**MW-103**
Sample #	**S-1**	**S-10**	**S-11**	**S-12**	**S-13**	**S-13b**	**S-15**	**S-16**	**S-17**	**S-18**
Depth Interval (ft)	**0 - 2**	**44 - 46**	**49 - 51**	**54 - 56**	**59 - 61**	**59 - 61**	**69 - 71**	**74 - 76**	**79 - 81**	**84 - 86**

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Diameter (mm)										
4.75	91.87	99.78	97.49	81.87	94.37	100.00	63.28	50.86	96.39	88.24
2	86.05	98.56	91.21	75.77	85.91	99.74	44.64	35.29	88.32	72.21
0.85	74.69	93.71	69.65	65.47	76.58	98.95	31.14	23.97	65.58	50.40
0.425	41.08	87.42	40.07	49.81	38.55	95.00	23.06	17.15	30.93	25.93
0.15	9.38	15.38	12.47	15.03	10.53	20.00	12.81	8.02	10.39	10.54
0.105	7.28	11.40	9.16	11.80	7.82	13.07	11.17	5.83	8.86	8.92
0.075	6.19	6.93	8.57	8.86	6.21	7.81	9.32	5.37	6.95	6.95

Well # Sample # Depth Interval (ft)	MW-103 S-19 89 - 91	MW-103 S-20 94 - 96	MW-103 S-21 99 - 101	MW-103 S-22 104 - 106	MW-103 S-23 109 - 111	MW-103 S-24 114 - 116	MW-103 S-26 124 - 126
Diameter (mm)							
4.75	94.16	92.93	99.98	99.95	92.91	63.56	99.72
2	87.31	86.48	99.39	97.15	88.75	46.02	97.95
0.85	69.86	61.62	95.66	76.22	78.16	34.31	93.76
0.425	31.18	50.16	48.57	42.90	55.83	26.20	78.00
0.15	12.48	18.40	6.18	19.04	23.43	16.10	26.56
0.105	10.63	13.61	4.22	16.47	18.79	13.52	17.10
0.075	8.02	9.95	2.43	12.63	12.27	11.29	12.69

Well #	MW-104	MW-104	MW-104	MW-104	MW-104	MW-104	MW-104	MW-104	MW-104	MW-104

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Sample #	S-1	S-2	S-3	S-4	S-5	S-6	S-7	S-8	S-9	S-10
Depth Interval (ft)	**1 - 9**	**9 - 11**	**14 - 16**	**19 - 21**	**24 - 26**	**29 - 31**	**34 - 36**	**39 - 41**	**44 - 46**	**49 - 51**
Diameter (mm)										
4.75	99.94	100.00	99.05	99.00	99.79	96.98	100.00	100.00	99.73	42.23
2	99.49	99.73	98.85	96.48	99.26	93.23	99.90	99.83	99.12	29.58
0.85	96.92	97.97	96.93	95.34	96.21	90.39	99.47	99.50	98.65	20.31
0.425	84.09	88.54	85.90	94.25	89.33	88.27	96.24	98.24	97.33	15.25
0.15	18.29	28.11	14.68	76.53	35.86	53.98	49.25	71.60	57.06	8.26
0.105	13.12	15.21	10.97	56.70	30.31	46.86	30.30	51.80	42.76	6.38
0.075	7.23	8.02	7.14	36.77	18.61	30.73	17.62	30.56	19.66	4.94

Well #	MW-105	MW-105	MW-105	MW-105	MW-105	MW-105	MW-105	MW-105	MW-105	MW-105
Sample #	**S-1**	**S-2**	**S-3**	**S-4**	**S-5**	**S-6**	**S-7**	**S-9**	**S-10**	**S-11**
Depth Interval (ft)	**0 - 2**	**5 - 7**	**9 - 11**	**14 - 16**	**19 - 21**	**24 - 26**	**29 - 31**	**39 - 41**	**44 - 46**	**49 - 51**
Diameter (mm)										
4.75	76.10	99.81	99.33	92.96	98.22	99.95	99.10	99.93	100.00	99.72
2	69.98	98.83	97.37	88.02	96.54	99.90	97.54	99.09	99.96	99.05
0.85	59.15	96.53	92.59	77.56	91.67	97.78	96.43	94.39	99.65	98.55
0.425	45.44	81.41	77.85	56.17	71.12	90.84	91.50	82.66	98.07	97.22
0.15	21.10	12.15	16.25	12.80	14.20	19.49	20.89	18.45	38.97	29.85
0.105	14.98	8.03	11.26	9.01	10.30	12.44	15.43	12.17	27.82	18.63
0.075	12.36	5.28	6.58	7.43	6.13	8.41	8.83	8.11	13.00	10.88

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Well #	MW-105	MW-105	MW-105
Sample #	S-13	S-14	S-15
Depth Interval (ft)	59 - 61	64 - 66	69 - 71
Diameter (mm)			
4.75	69.83	99.94	99.95
2	56.39	98.86	99.81
0.85	41.22	96.17	90.78
0.425	29.55	89.87	50.86
0.15	14.02	33.12	6.26
0.105	11.67	21.05	4.11
0.075	8.96	13.04	2.67

Well #	MW-106	MW-106	MW-106	MW-106	MW-106	MW-106	MW-106	MW-106	MW-106	MW-106
Sample #	S-1	S-2	S-3	S-4	S-5	S-6	S-7	S-8	S-9	S-10
Depth Interval (ft)	0 - 3	5 - 7	9 - 11	14 - 16	19 - 21	24 - 26	29 - 31	34 - 36	39 - 41	44 - 46
Diameter (mm)										
4.75	83.66	100.00	98.87	99.96	100.00	99.99	99.99	99.95	99.98	100.00
2	70.92	99.34	98.23	99.66	99.98	99.97	99.97	97.36	99.57	100.00
0.85	49.88	94.00	97.73	97.71	99.80	99.63	99.63	95.70	98.31	99.66
0.425	26.06	75.45	94.96	92.21	94.29	96.55	96.55	95.20	97.46	98.76
0.15	10.35	10.81	37.70	44.09	23.08	26.47	26.47	76.30	75.12	52.22
0.105	7.62	7.78	27.74	25.46	16.56	14.40	14.40	60.90	51.72	43.22

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0.075	6.13	3.89	22.32	14.16	8.83	8.31	8.31	36.14	29.32	25.24

Well # **Sample #** **Depth Interval (ft)**	**MW-106** **S-11** **49 - 51**	**MW-106** **S-12** **54 - 56**	**MW-106** **S-13** **59 - 61**	**MW-106** **S-14** **64 - 66**	**MW-106** **S-16** **74 - 76**
Diameter (mm)					
4.75	100.00	100.00	81.78	57.60	65.10
2	99.72	99.96	68.02	43.37	50.93
0.85	98.86	99.94	55.66	25.75	43.49
0.425	95.73	99.37	45.52	16.01	39.21
0.15	32.80	29.32	23.43	3.92	30.51
0.105	24.38	22.85	14.80	2.58	28.39
0.075	13.68	12.18	10.76	0.56	25.64

Well # **Sample #** **Depth Interval (ft)**	**MW-107** **S-1** **0 - 2**	**MW-107** **S-2** **5 - 7**	**MW-107** **S-3** **9 - 11**	**MW-107** **S-4** **14 - 16**	**MW-107** **S-5** **19 - 21**	**MW-107** **S-6** **24 - 26**	**MW-107** **S-7** **29 - 31**	**MW-107** **S-8** **34 - 36**
Diameter (mm)								
4.75	99.04	92.60	95.13	100.00	100.00	98.17	99.57	45.67
2	94.96	85.04	94.27	99.90	99.71	96.09	98.70	32.86
0.85	87.21	80.13	92.64	98.79	90.26	90.56	89.56	26.03

0.425	65.01	75.64	87.58	94.11	18.80	25.73	20.61	22.52
0.15	23.69	60.64	45.97	27.42	1.29	0.37	0.59	16.29
0.105	18.05	53.57	29.16	13.95	1.07	0.23	0.35	15.42
0.075	13.82	34.12	16.55	7.99	0.50	0.06	0.16	13.86

Well #	**MW-108**	**MW-108**	**MW-108**	**MW-108**	**MW-108**	**MW-108**	**MW-108**	**MW-108**
Sample #	**S-1**	**S-8**	**S-9**	**S-12**	**S-14**	**S-15**	**S-16**	**S-17**
Depth Interval (ft)	**0 - 2**	**34 - 36**	**39 - 41**	**54 - 56**	**64 - 66**	**69 - 71**	**74 - 76**	**79 - 81**
Diameter (mm)								
4.75	97.60	99.96	100.00	60.31	94.79	74.07	42.42	77.90
2	59.99	99.89	99.51	48.22	83.74	63.44	33.83	68.60
0.85	39.43	98.86	94.00	33.80	69.24	50.08	28.34	60.05
0.425	29.63	94.67	73.44	21.97	56.17	38.98	23.55	48.21
0.15	16.56	33.02	7.67	9.89	18.01	15.87	9.73	19.28
0.105	14.81	16.27	5.16	8.17	10.28	11.67	7.83	16.45
0.075	11.47	7.86	3.03	6.44	9.65	8.25	4.94	12.20

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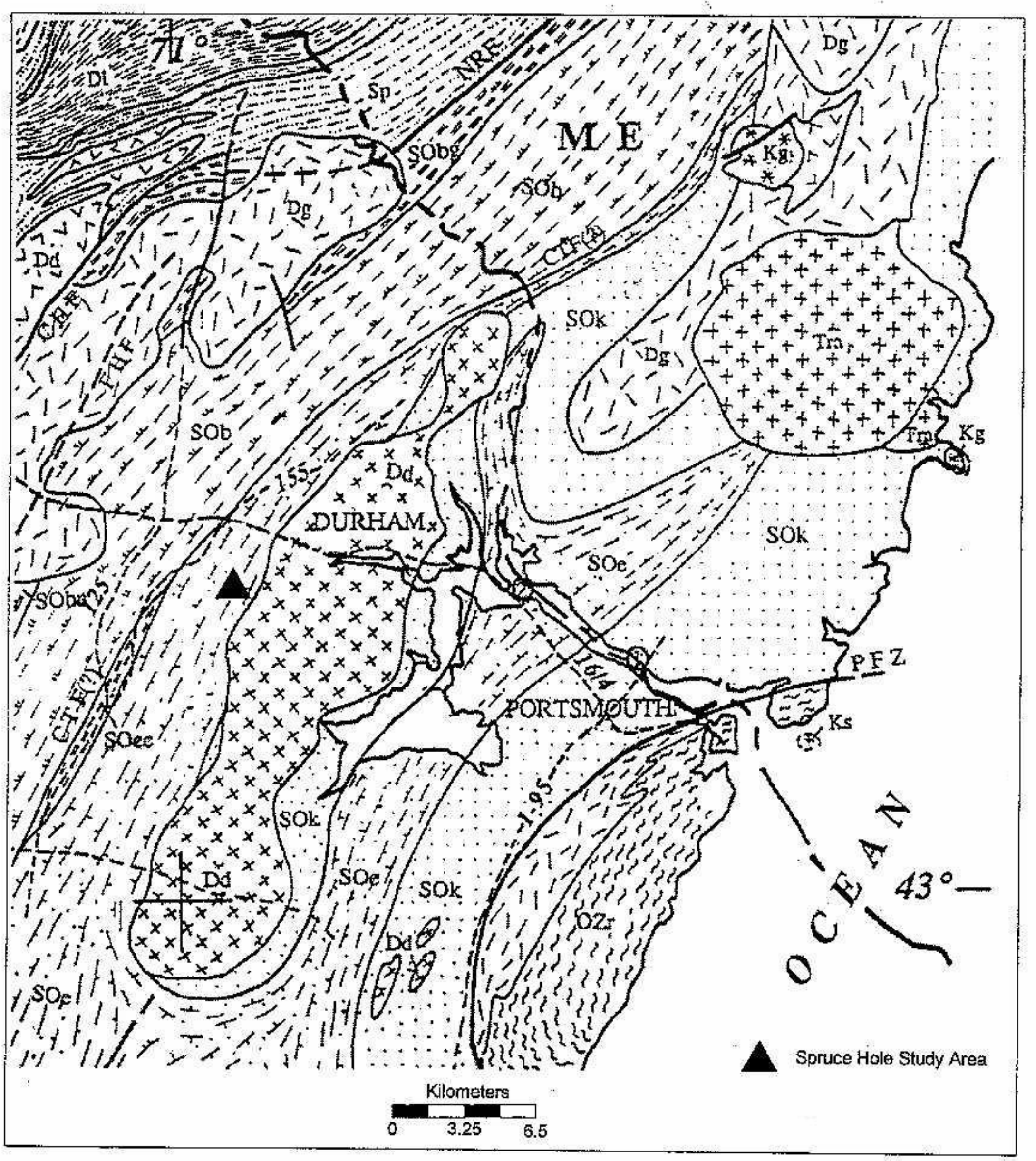
Appendix 8 Geology and Geophysics

Significant field efforts were completed during the performance of this project. Included were geophysical efforts aimed at depicting the surficial and bedrock geology of the Spruce Hole formation. The Masters' theses by Kerwin and Wolf should be read for details on the geophysical efforts and the interpretation of the data. The figures in this Appendix were obtained from the theses of Flynn, Kerwin, and Wolf.



Stratified Rocks of the Merrimack Group
SOk Kittery Formation
SOe Eliot Formation
SOec Calef Member of the Eliot Formation
SOb Berwick Formation
SObu Upper (?) Member of the Berwick Fm
SObg Gove or Gonic Member

Mylonitized Rocks of the Rye Block
OZr Rye Formation

Intrusive Rocks
Kg Gabbros-Cape Neddick and tatnick Hills
Tra Granite and syenite-Mt. Agamenticus
Dg Biotite and two-mica granite and granodiorite
Dd Diorite and gabbro-Exeter

Faults
PFZ Porstmouth Fault Zone
NRF Nonesuch River Fault
FHF Flint Hill Fault
CHF Campbell Hill Fault
CTF Calef "Thrust Fault" (?)

Figure 8-1. Bedrock Geologic Map Within the Study Area (Fargo and Bothner, 1995).

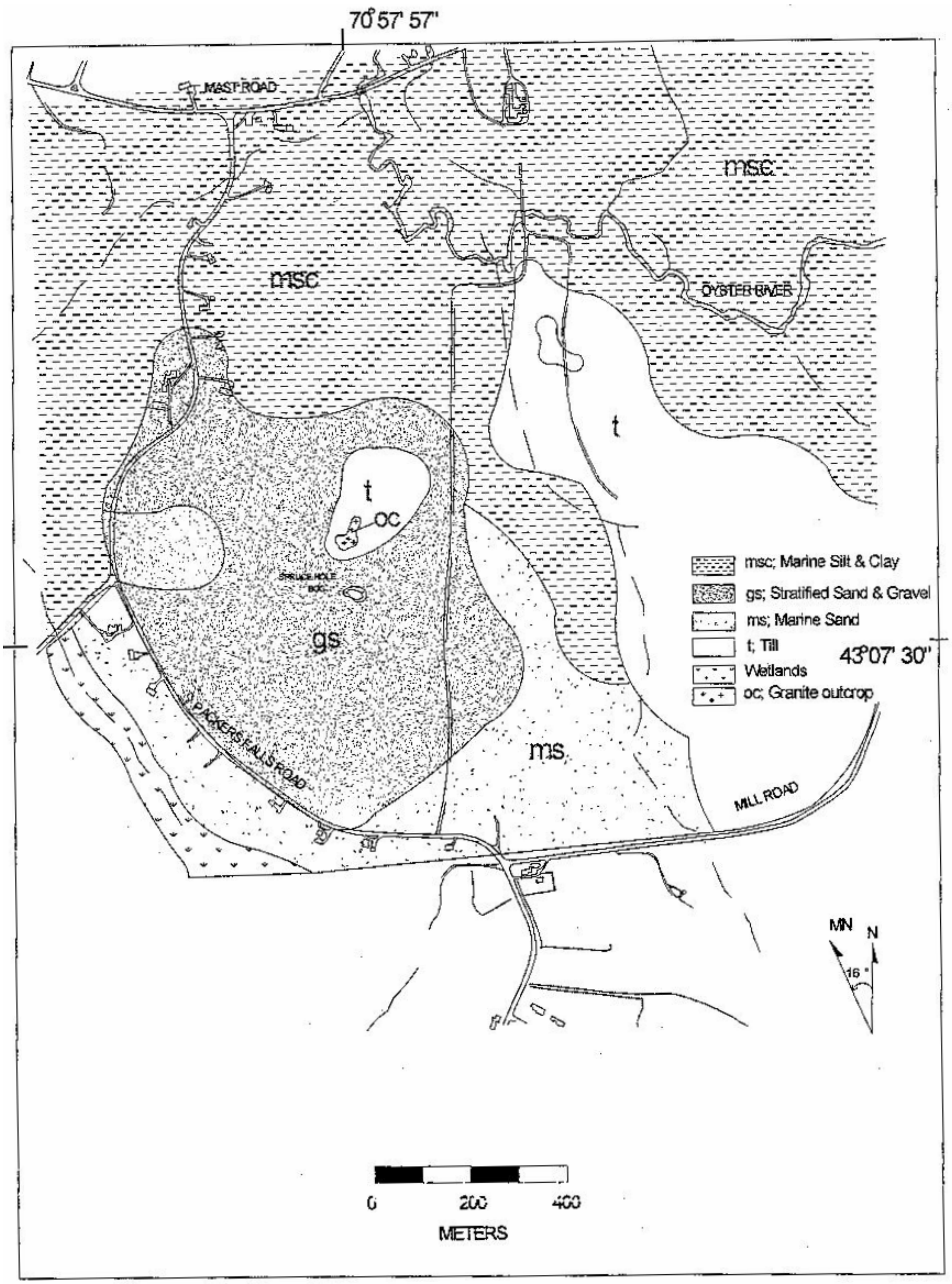


Figure 8-2. Surficial Geologic Map at the Spruce Hole Formation (Koteff, 1989).

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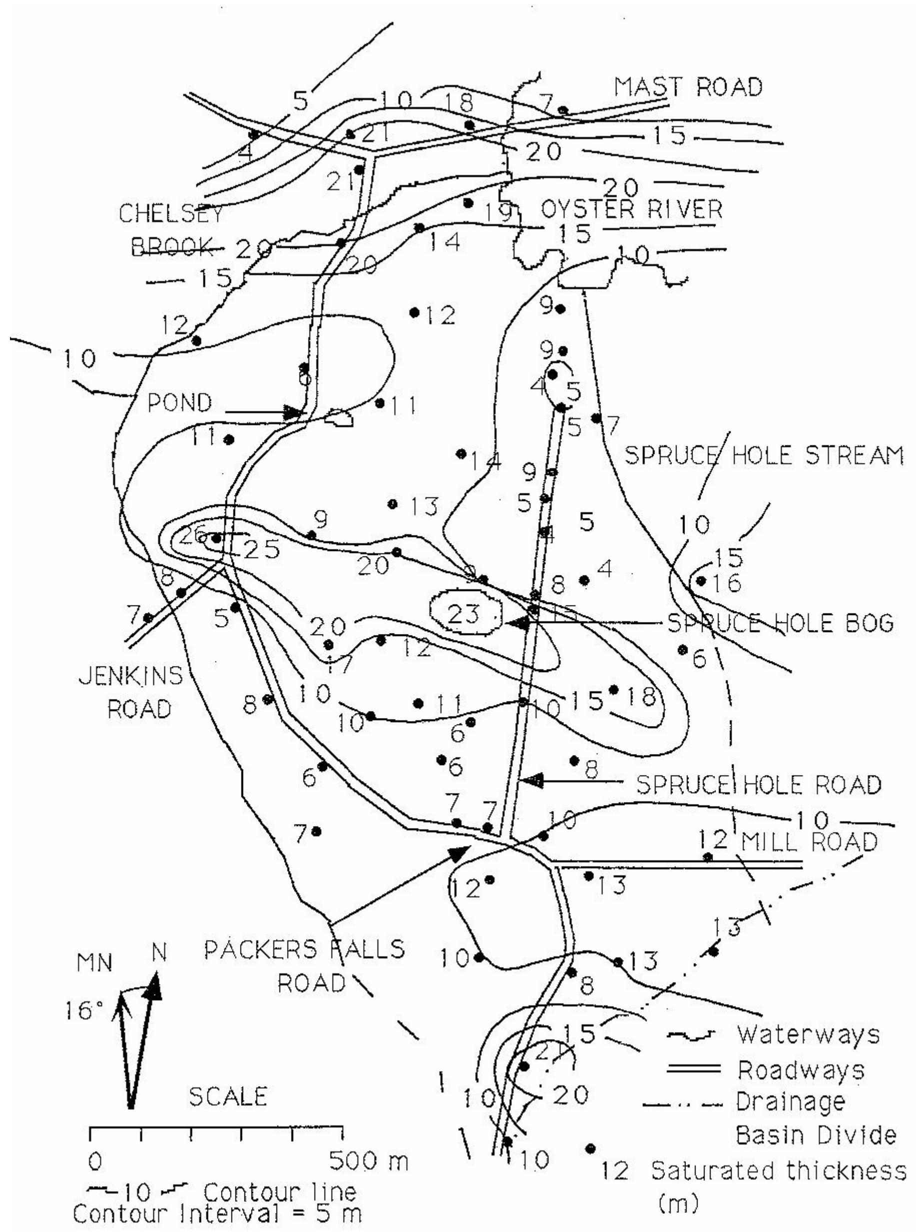

Figure 8-3. Saturated Thickness Contour Map from Seismic Refraction Survey (Kerwin, 1993).

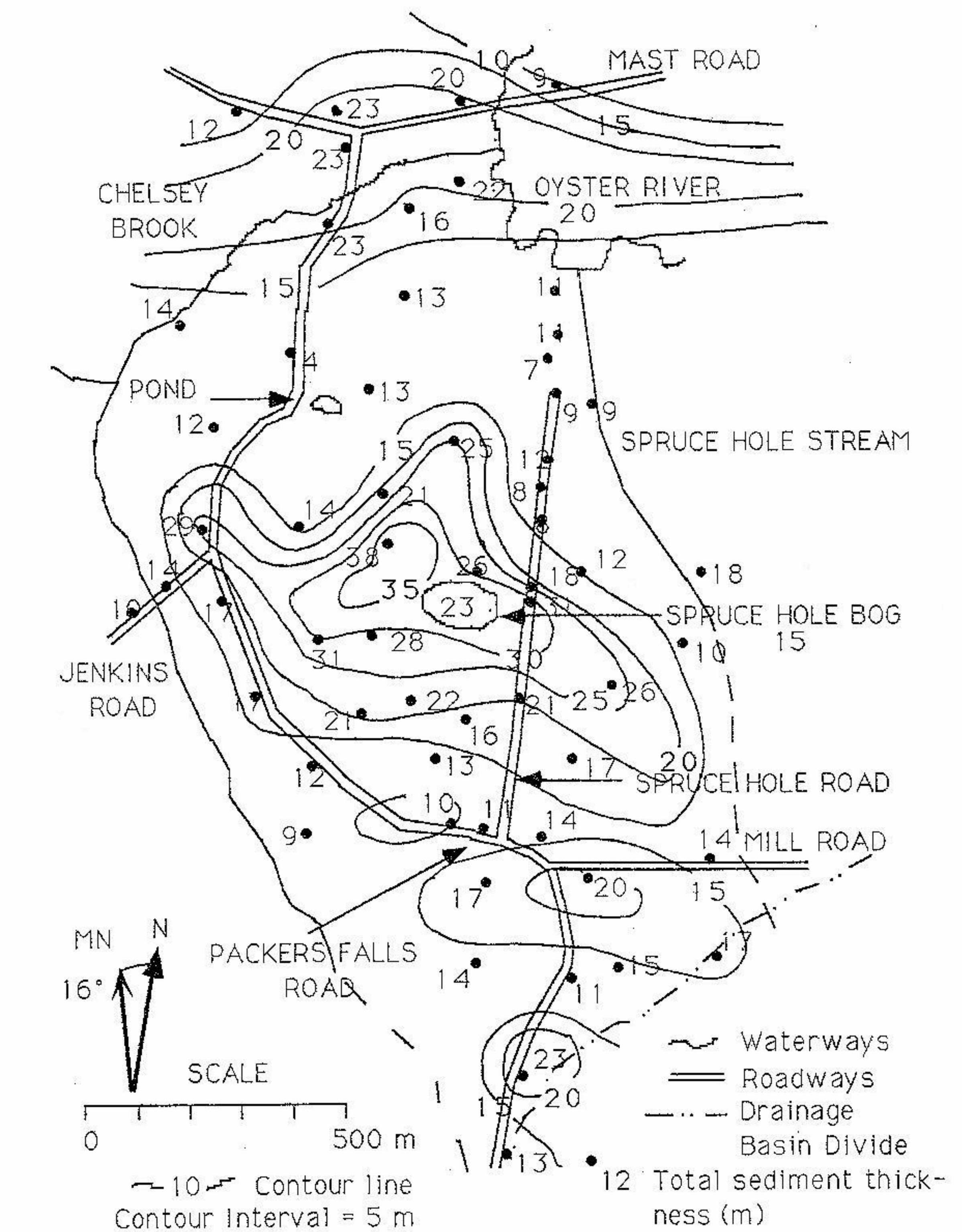

Figure 8-4. Total Sediment Thickness Contour Map From Seismic Refraction Survey (Kerwin, 1993).

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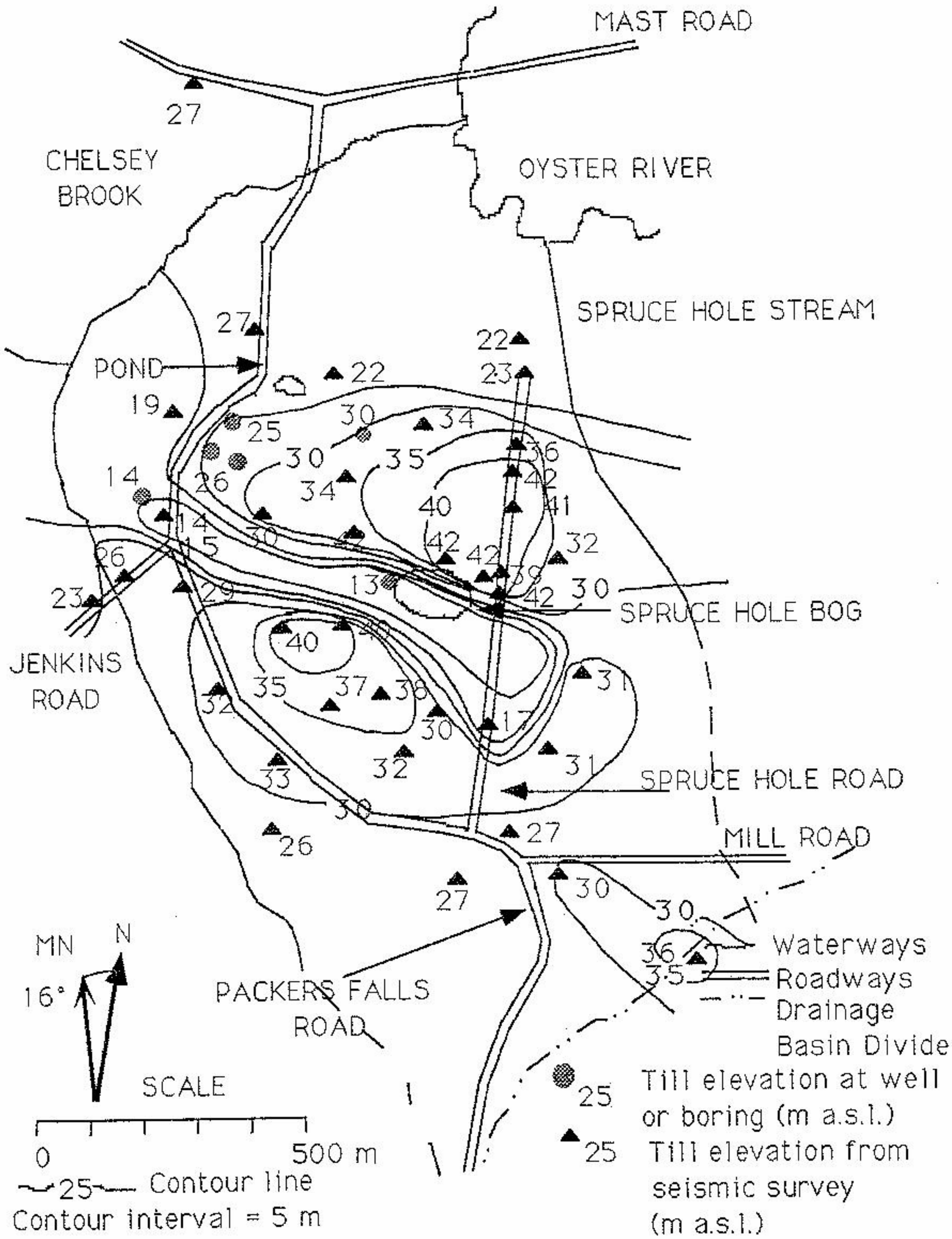

Figure 8-5. Till Elevation Contour Map From Seismic Refraction Survey (Kerwin, 1993).

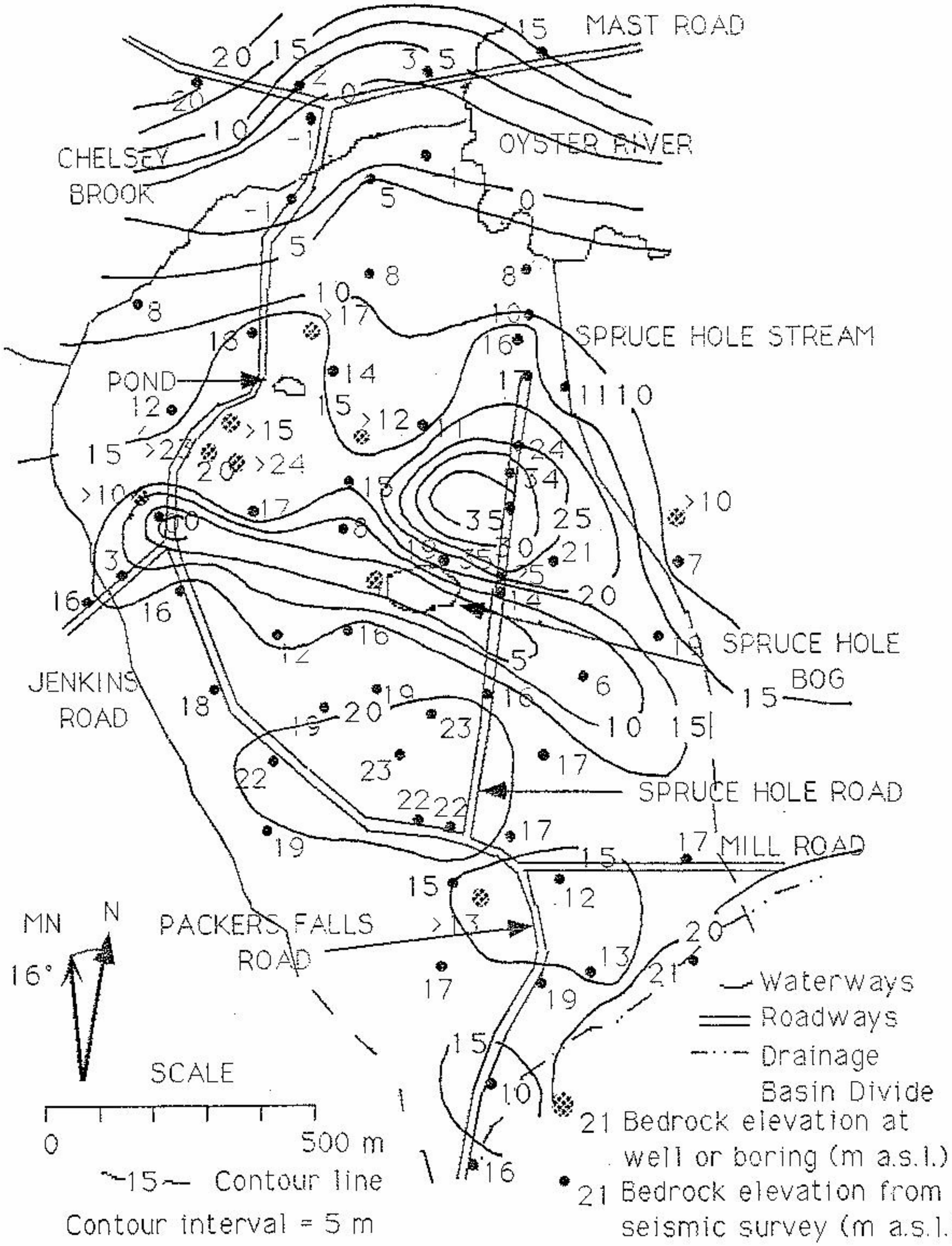

Figure 8-6. Bedrock Elevation Contour Map From Seismic Refraction Survey (Kerwin, 1993).

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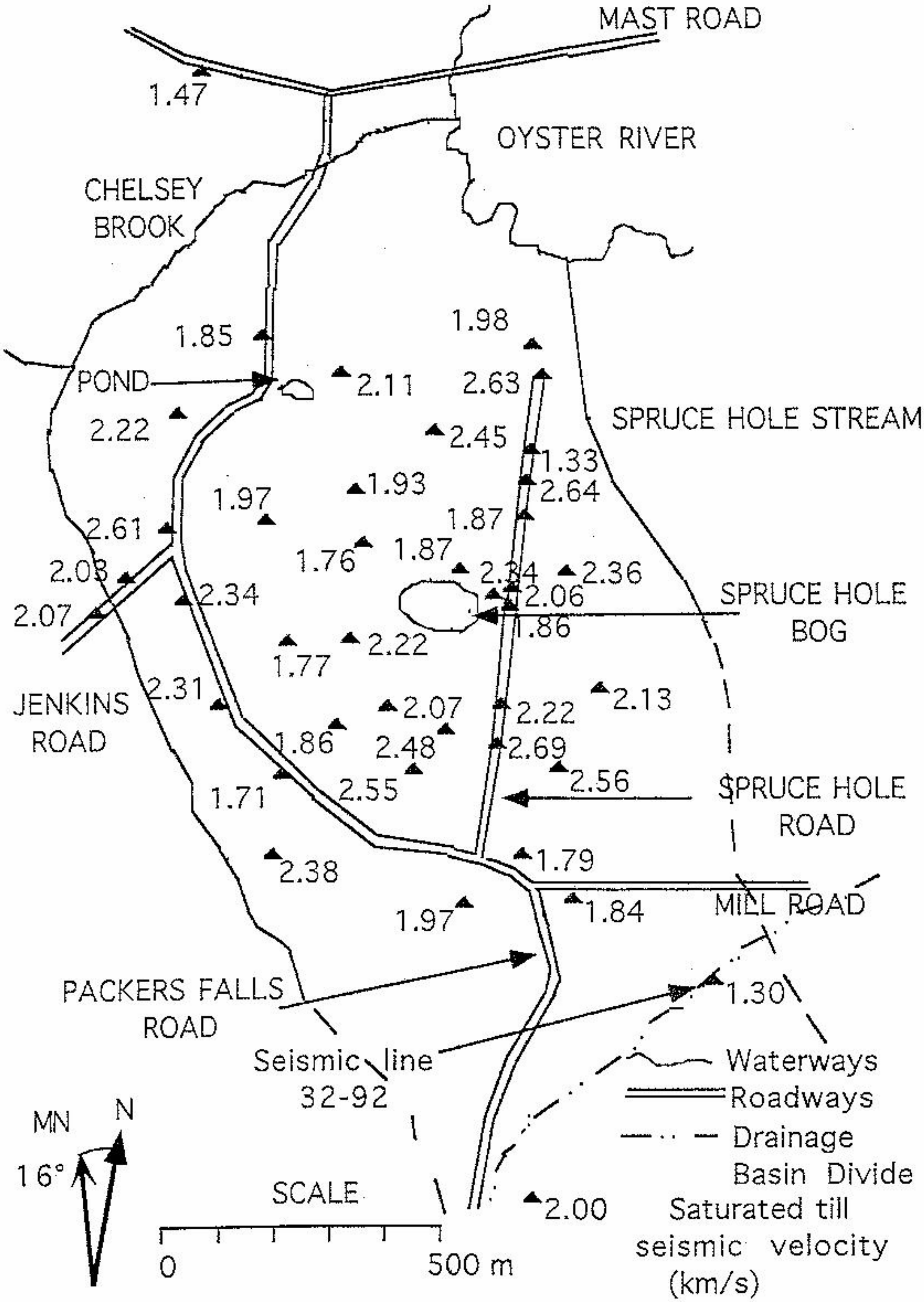

Figure 8-7. Saturated Till Velocity Map From Seismic Refraction Survey (Kerwin, 1993).

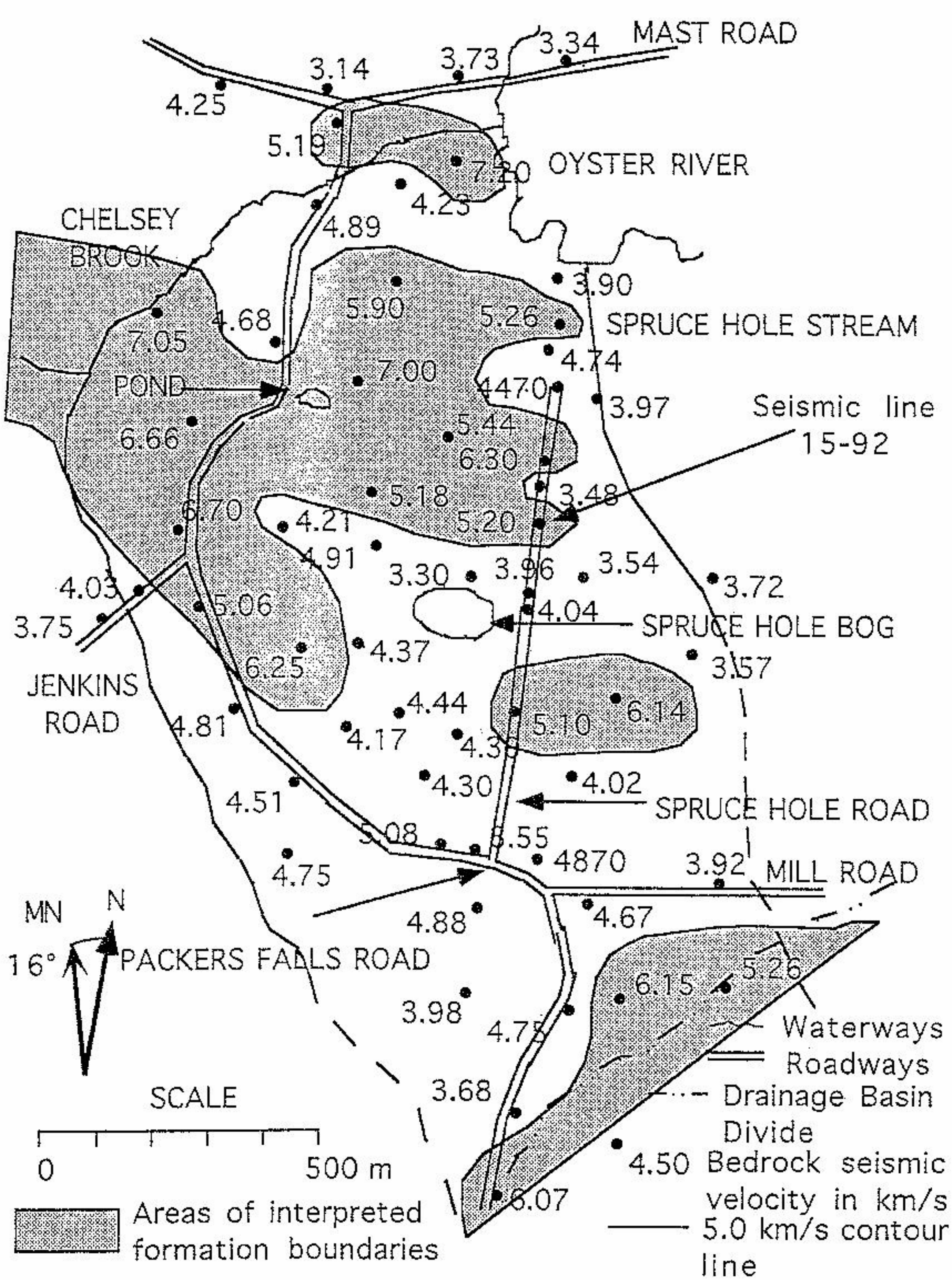

Figure 8-8. Bedrock Velocity Map, With Interpreted Formation Boundaries, From Seismic Refraction Survey (Kerwin, 1993).

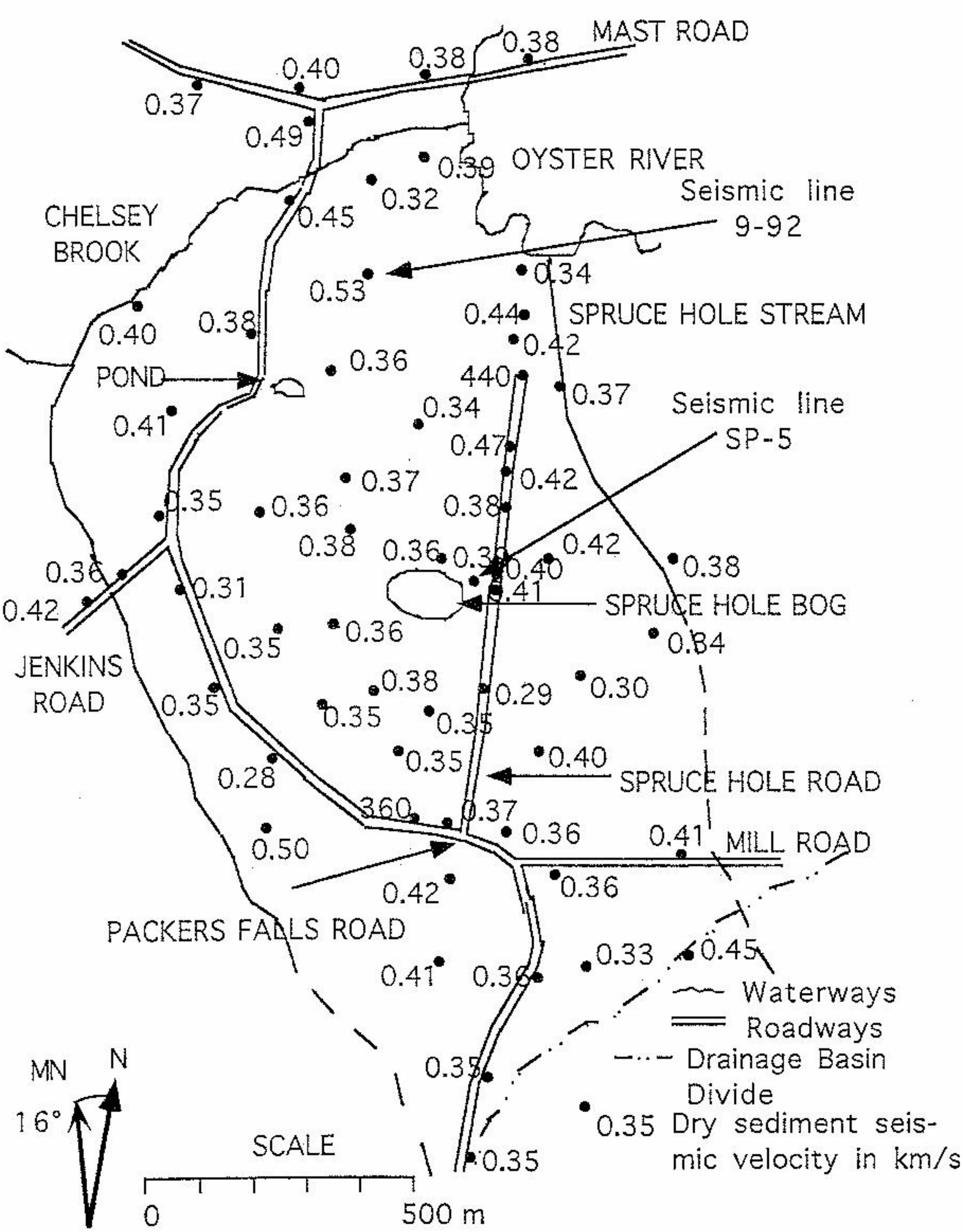

Figure 8-9. Dry Sediment Velocity Map From Seismic Refraction Survey (Kerwin, 1993).

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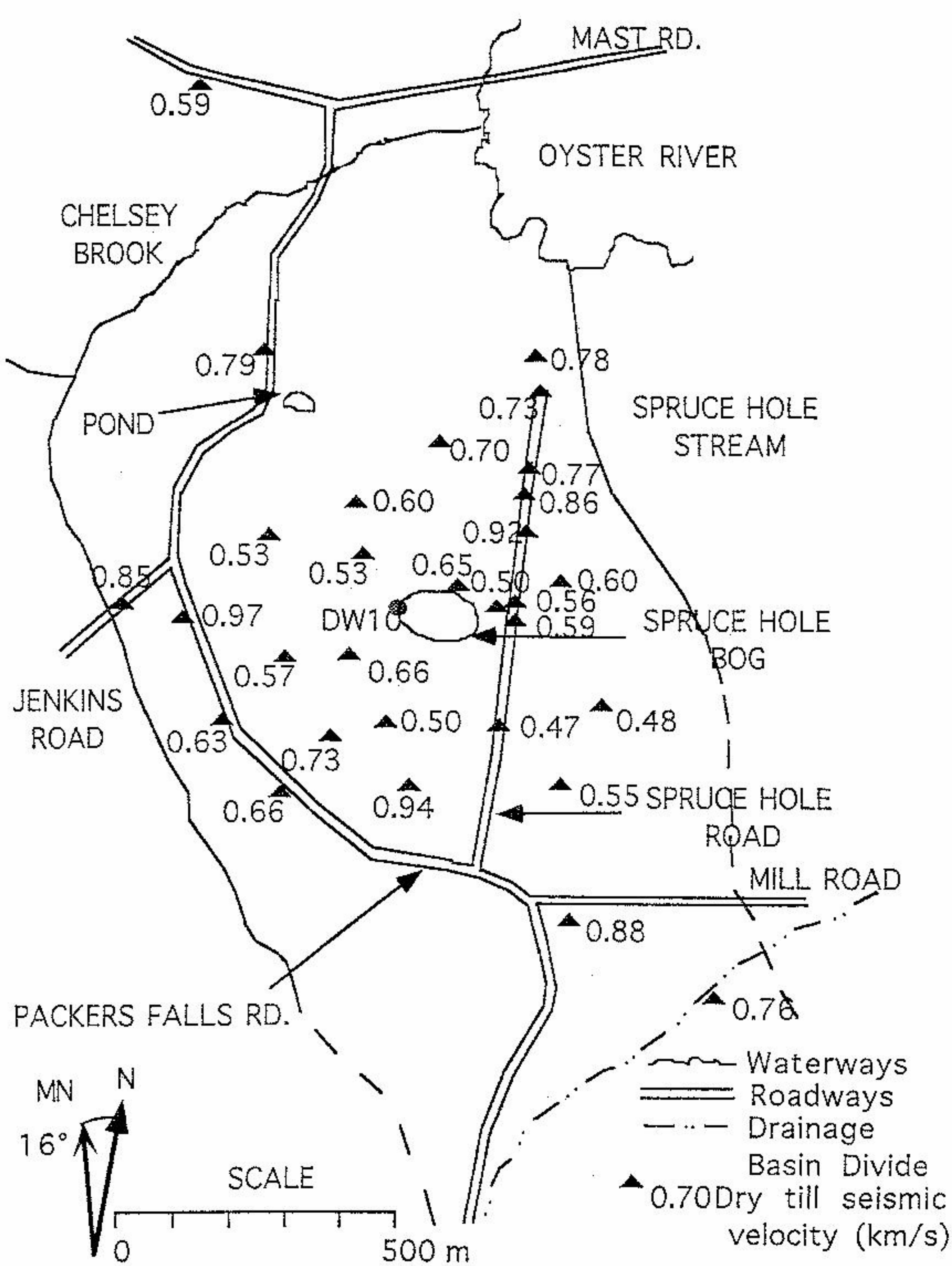

Figure 8-10. Dry Till Velocity Map From Seismic Refraction Survey (Kerwin, 1993).

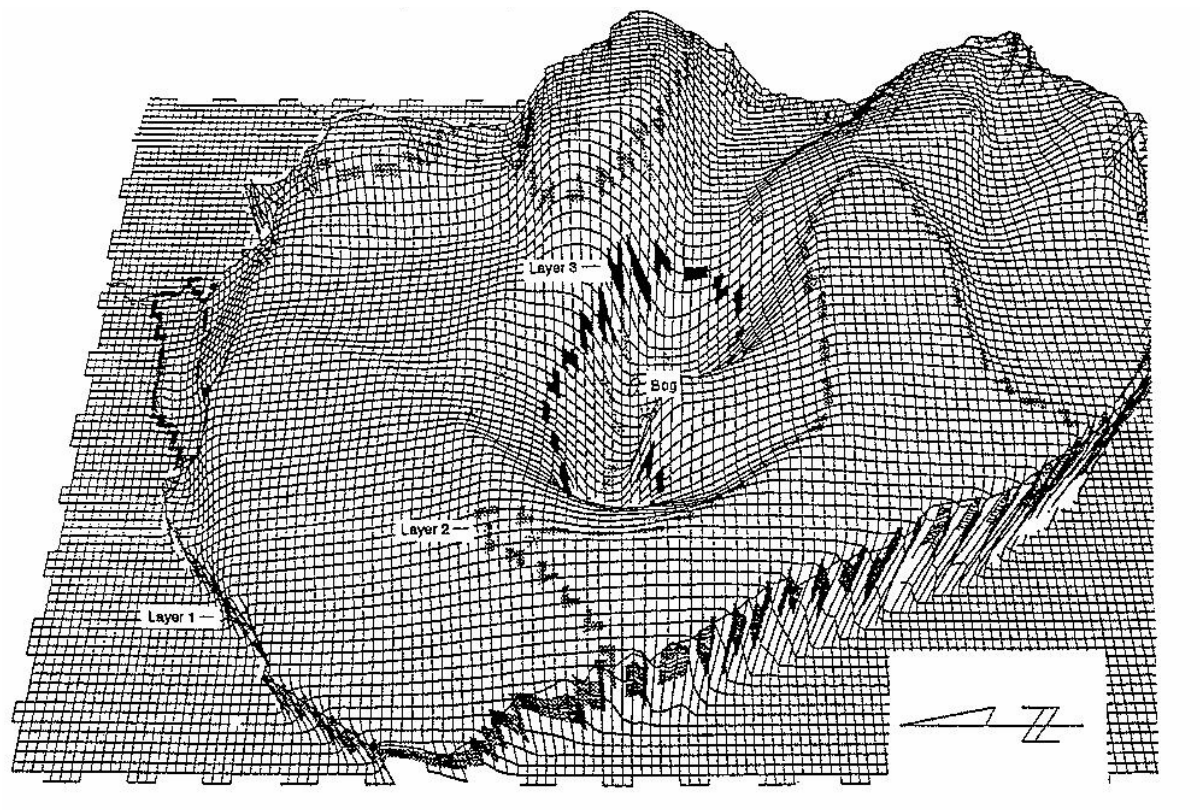

Figure 8-11. Three Dimensional Depiction of the Bedrock Surface Below the Spruce Hole Formation Overburden – Looking East (Flynn, 1996).

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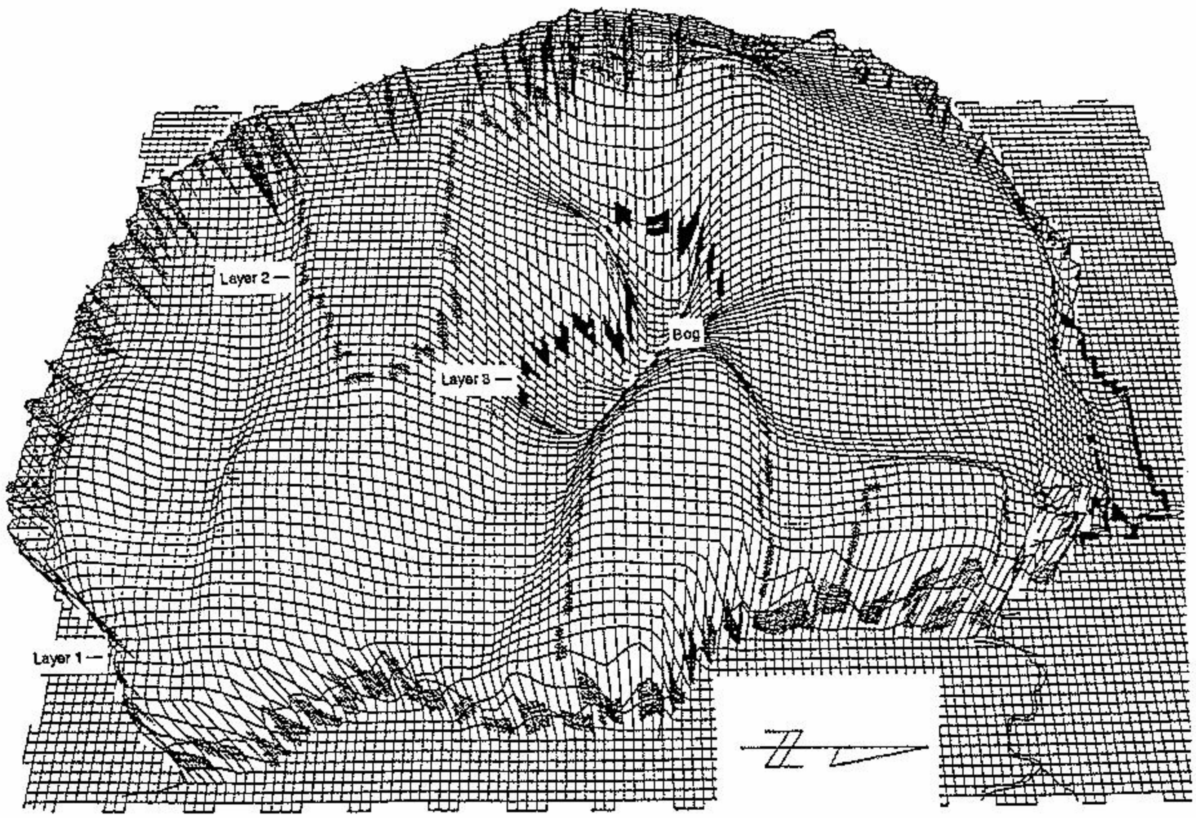

Figure 8-12. Three Dimensional Depiction of the Bedrock Surface Below the Spruce Hole Formation Overburden – Looking West (Flynn, 1996).

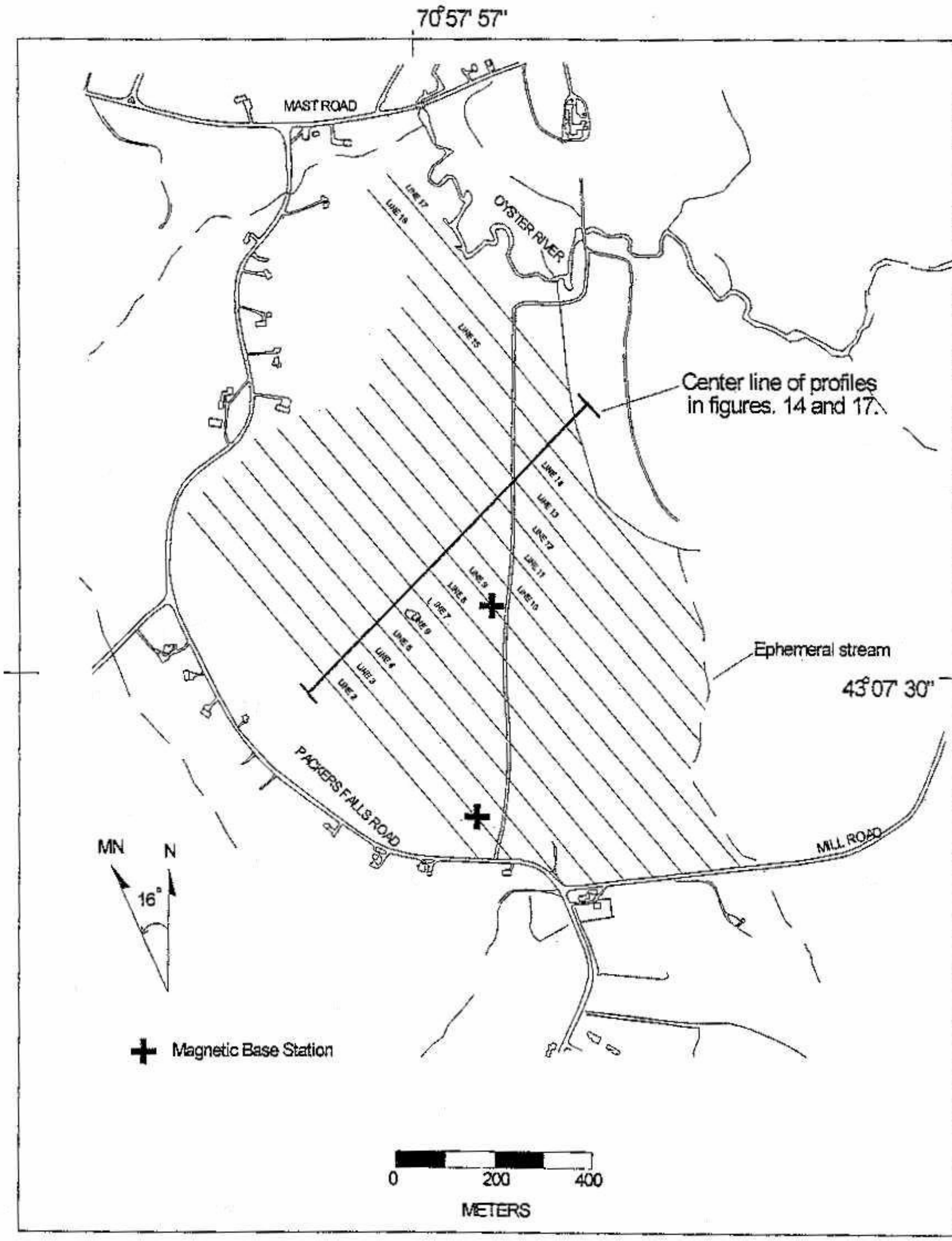

Figure 8-13. Geophysical Survey Grid for Figures 8-14 through 8-20 (Wolf, 1997).

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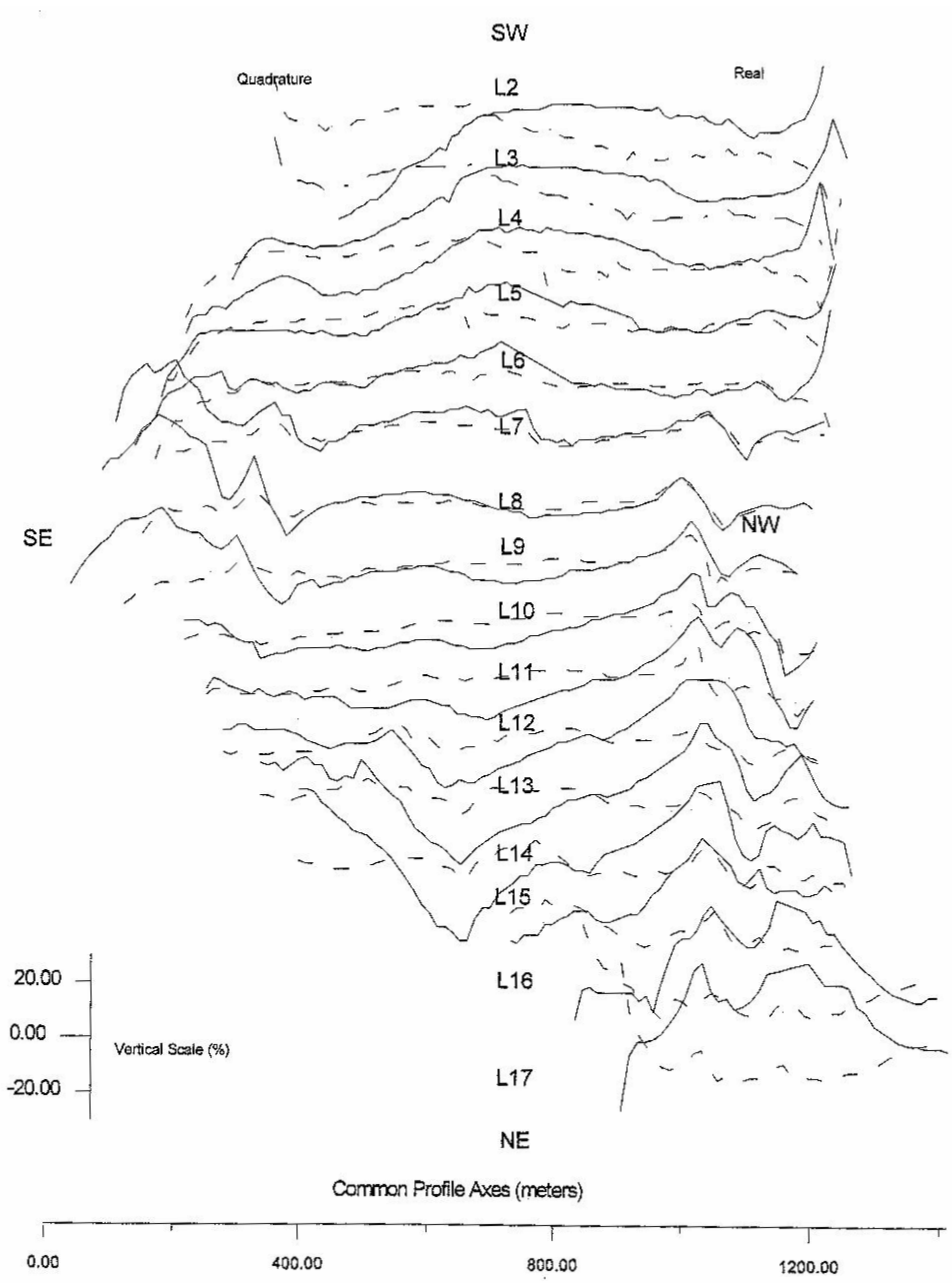

Figure 8-14. VLF Field Data Profiles (Wolf, 1997).

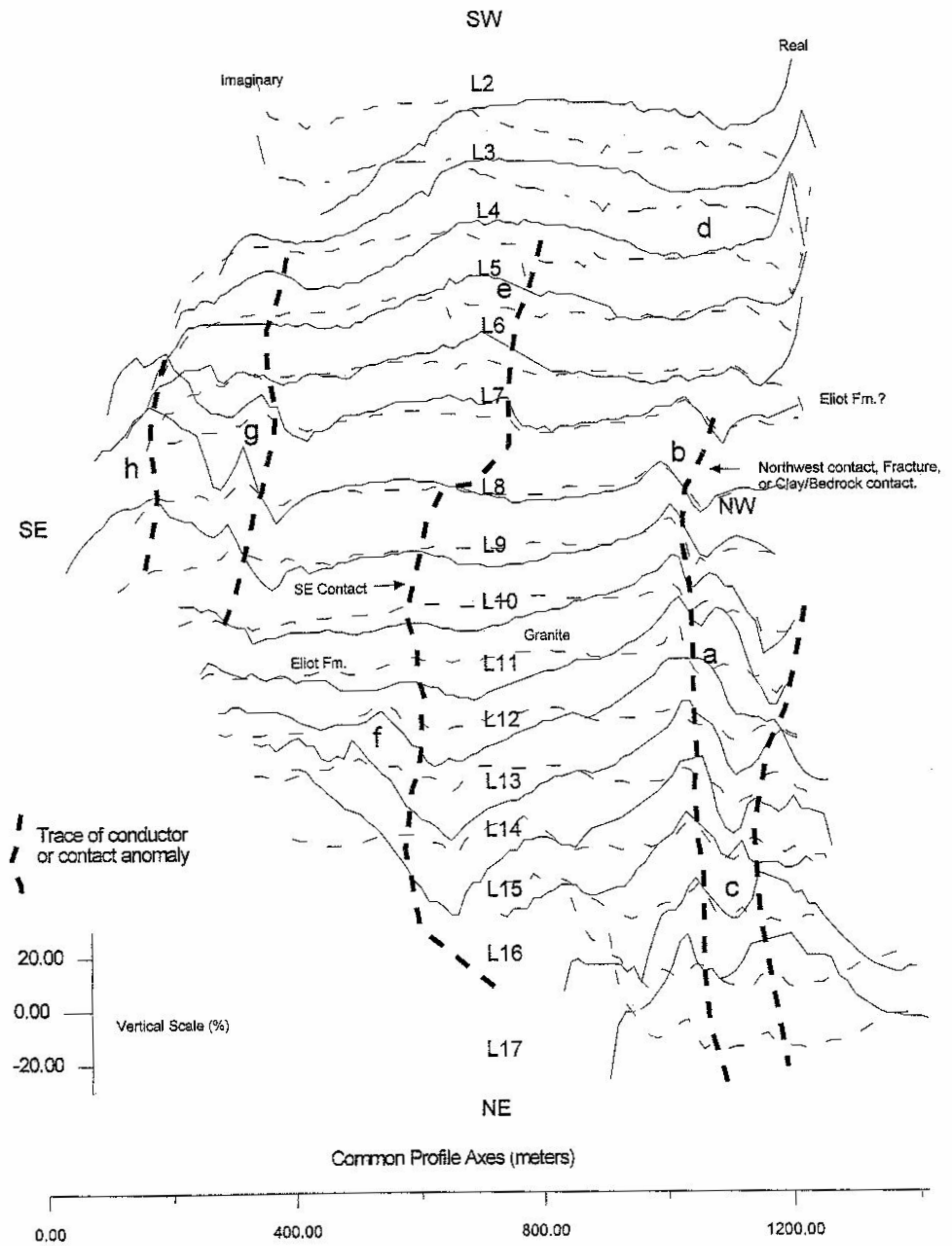

Figure 8-15. Interpreted VLF Field Data Profiles (Wolf, 1997).

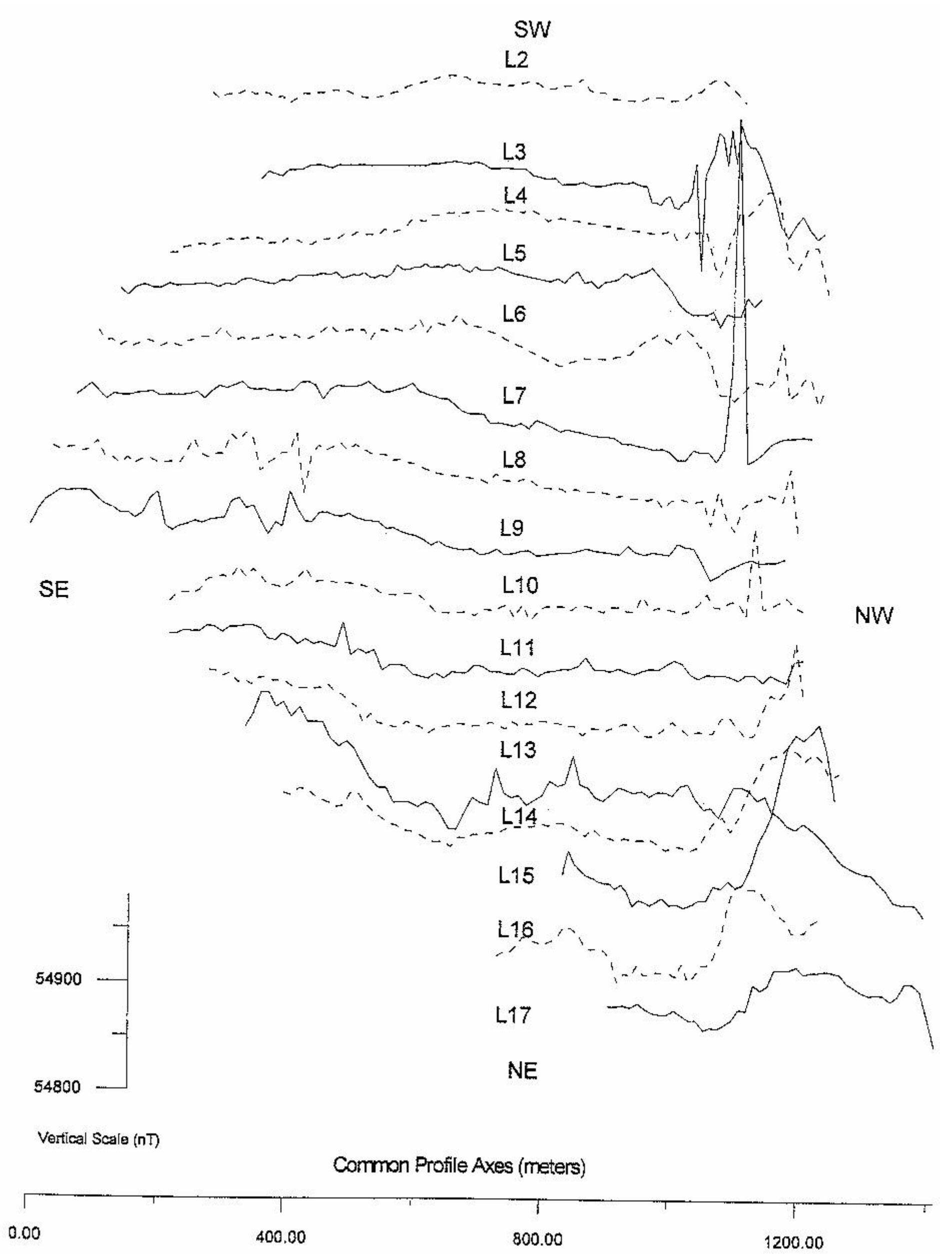

Figure 8-16. Magnetic Field Data Profiles (Wolf, 1997). Even-numbered magnetic profiles are dashed to aid in distinguishing between over-lapping anomalies.

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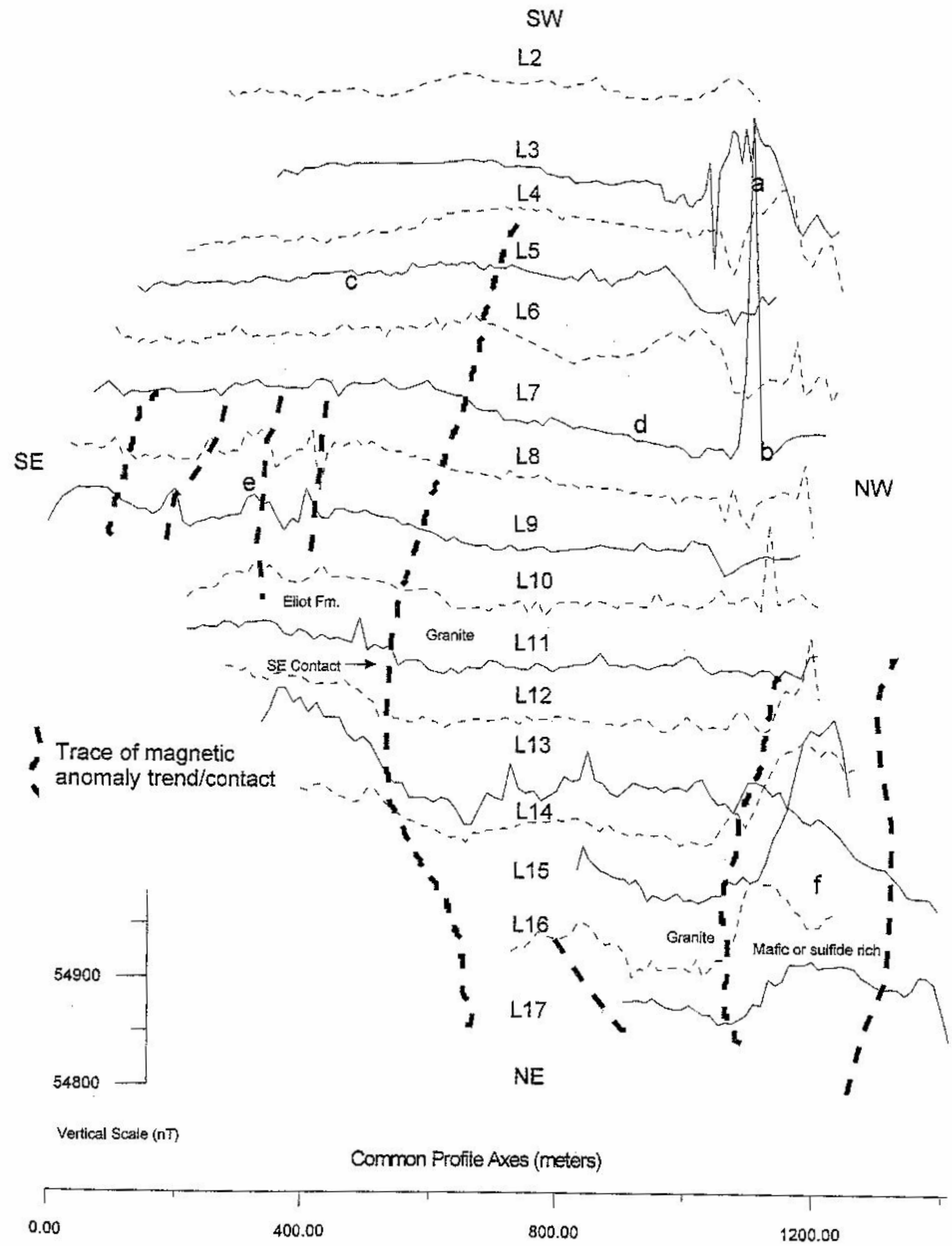

Figure 8-17. Interpreted Magnetic Field Data Profiles (Wolf, 1997).

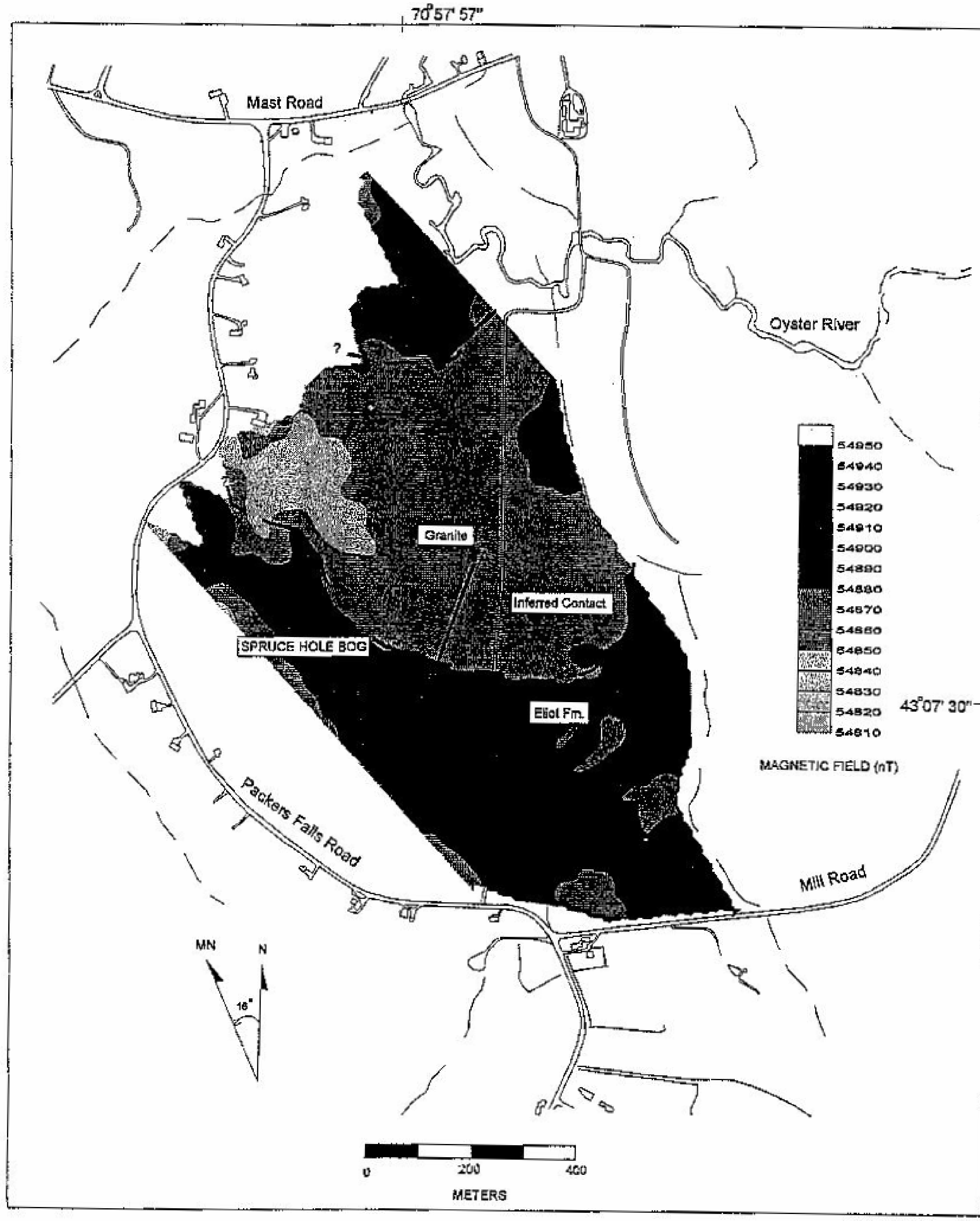

Figure 8-18 Total Field Magnetic Map (Wolf, 1997).

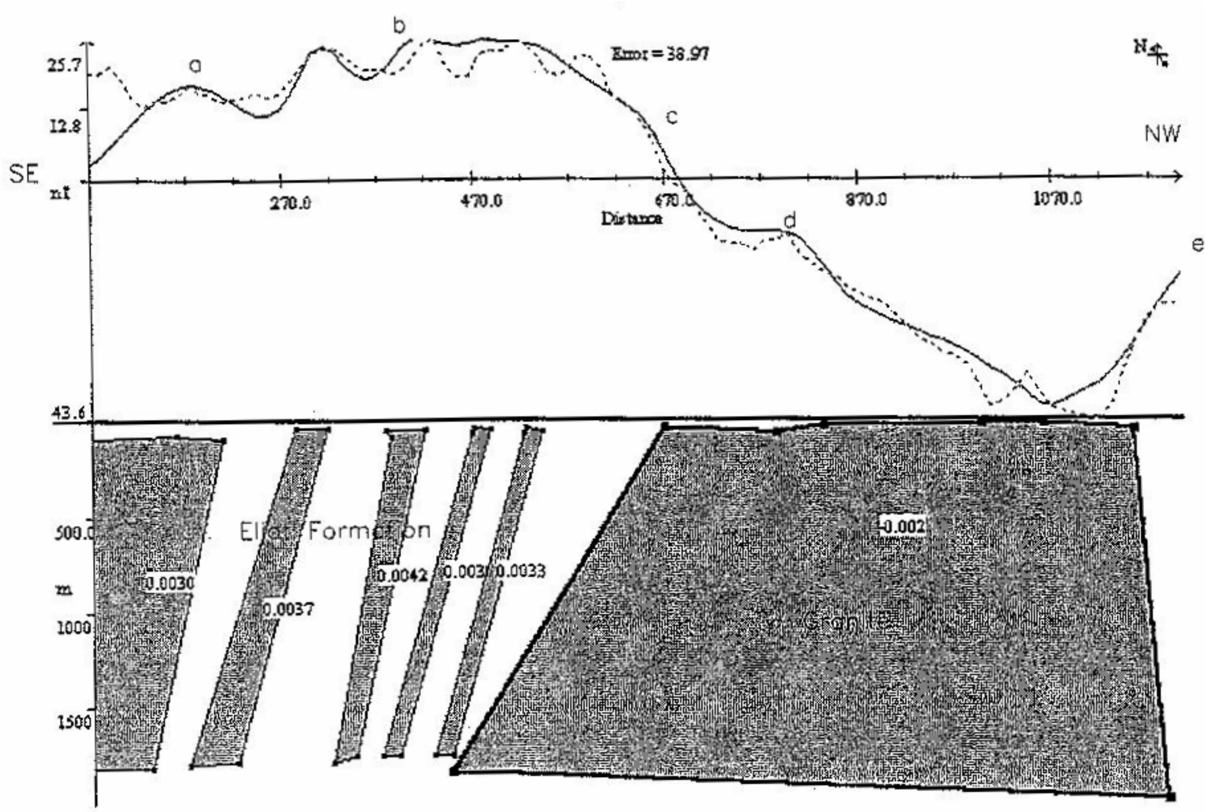

Figure 8-19. Bedrock Geologic Model Based on Magnetic Line L7 (Wolf, 1997). The dashed line is the smoothed data profile. The solid line is the calculated magnetic anomaly for the bedrock polygons displayed in the lower portion of the figure.

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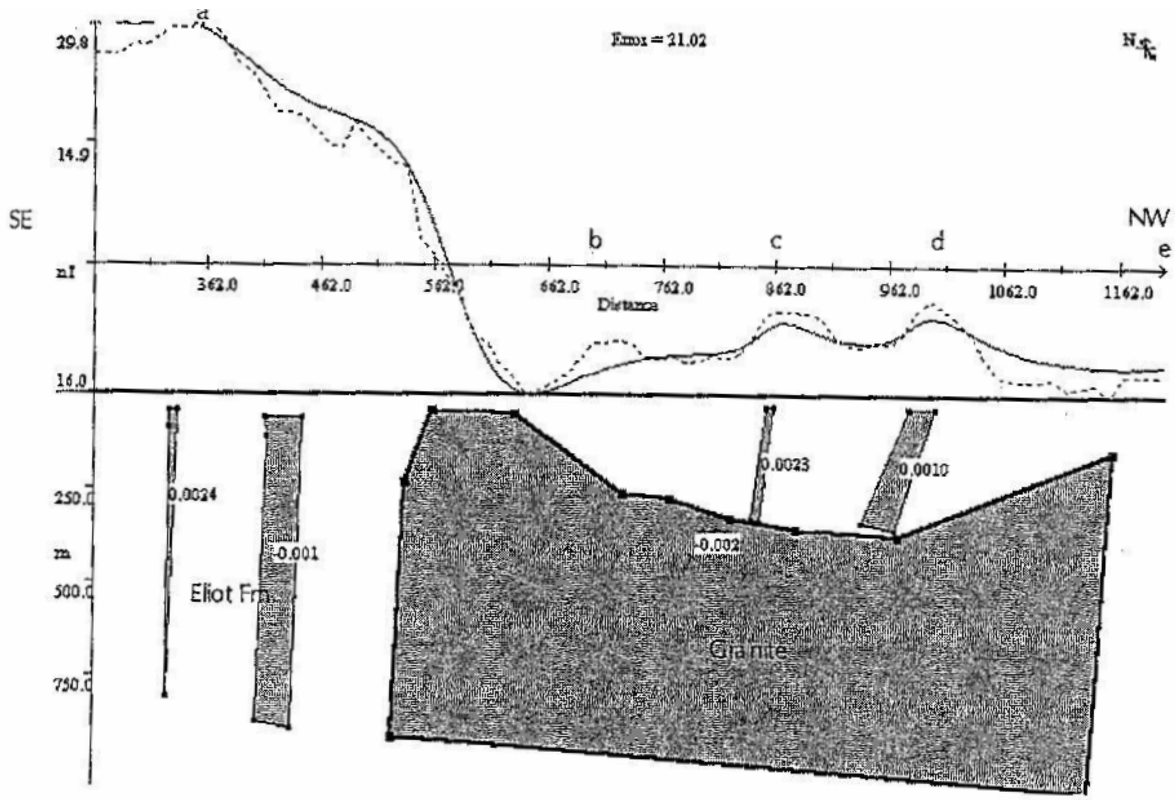

Figure 8-20. Bedrock Geologic Model Based on Magnetic Line L11 (Wolf, 1997). The dashed line is the smoothed data profile. The solid line is the calculated magnetic anomaly for the bedrock polygons displayed in the lower portion of the figure.

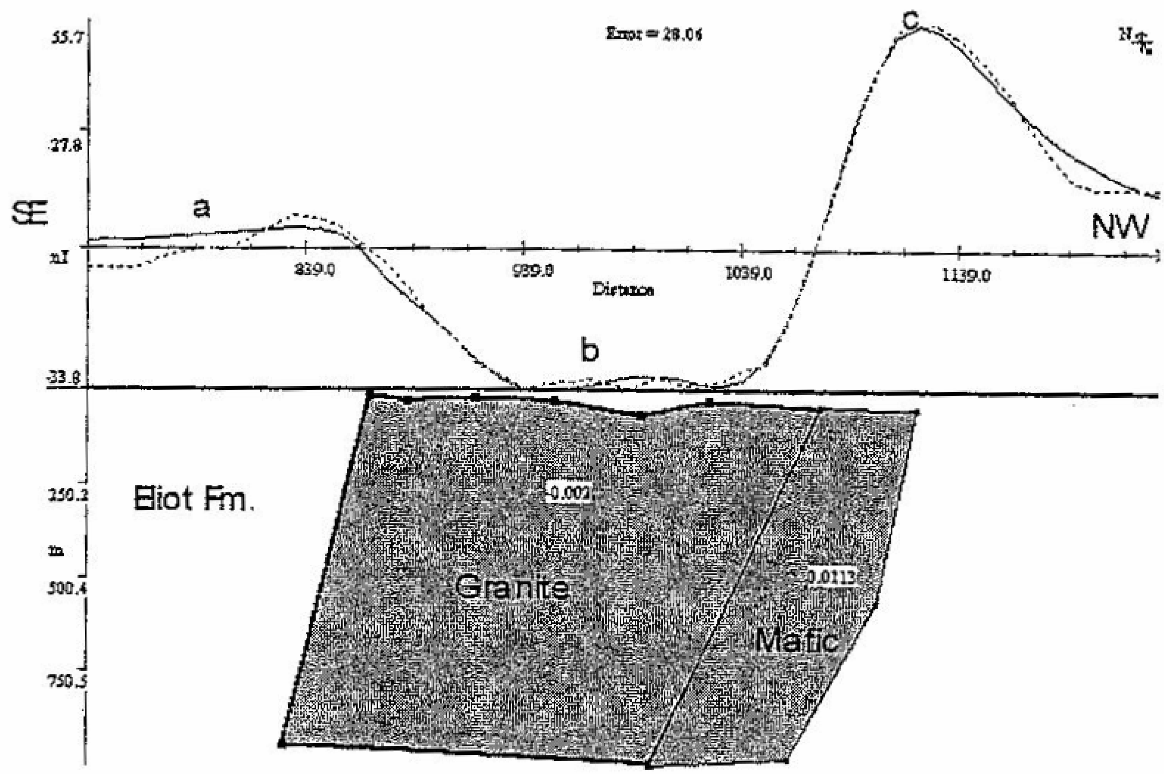

Figure 8-21. Bedrock Geologic Model Based on Magnetic Line L15 (Wolf, 1997). The dashed line is the smoothed data profile. The solid line is the calculated magnetic anomaly for the bedrock polygons displayed in the lower portion of the figure.

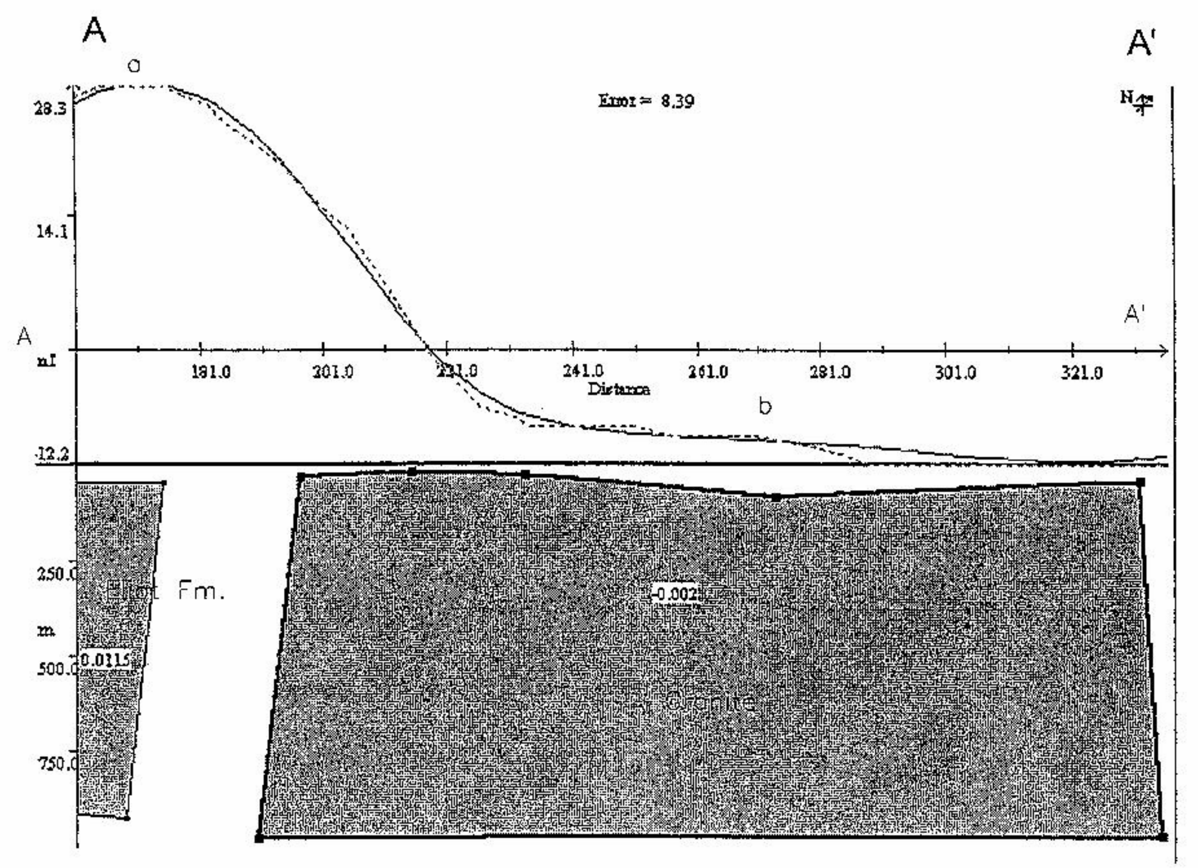

Figure 8-22. Bedrock Geologic Model of Profile A-A' in Figure 8-23 (Wolf, 1997). The dashed line is the smoothed data profile. The solid line is the calculated magnetic anomaly for the bedrock polygons displayed in the lower portion of the figure.

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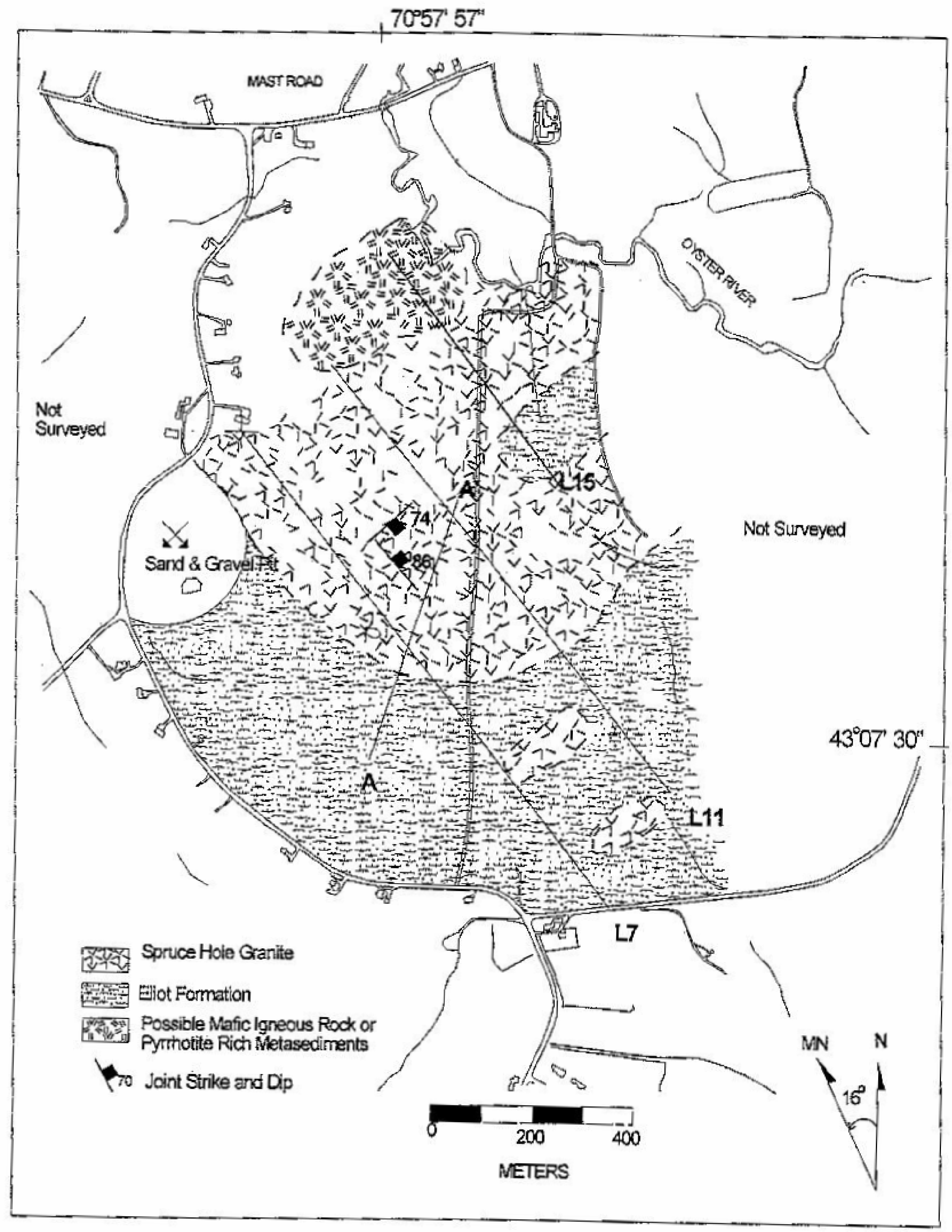

Figure 8-23. Geologic Map Based on Geophysical Data and Field Observations.

Appendix 9. **BIOLOGICAL STUDIES AT SPRUCE HOLE BOG**
FINAL REPORT

By

Scott D. Miller and Thomas D. Lee

PART 1. INTRODUCTION

1.1 Background and Objectives

Spruce Hole bog is the only remaining intact "kettlehole" bog in southeastern New Hampshire. Its uniqueness has been recognized by the National Park Service, which in 1972 designated the bog a National Natural Landmark. As bogs are ecosystems whose species composition is greatly influenced by water table characteristics and chemical composition of incoming water, development that impacts these variables can alter species composition and biological diversity of the community. Given the possible use of the Spruce Hole aquifer as a water source for Durham, questions have been raised about the possible impact of such development on Spruce Hole Bog.

Assessment of potential effects of development on any ecosystem first requires quantitative baseline information on the structure and natural dynamics of the biological community. Unfortunately, when the Spruce Hole aquifer became an issue in the late 1980's, relatively little was known about the vegetation, flora, and fauna of the bog. Consequently, the objectives of our research at Spruce Hole were to (1) determine what information was presently known about the distribution, abundance, and environmental relations of organisms in Spruce Hole, (2) produce a complete flora of the bog, (3) describe and map plant communities in the bog, (4) determine the recent history of bog vegetation, focusing on white pine, and (5) establish permanent vegetation plots for long-term monitoring.

1.2 What is a bog?

Bogs are just one type of peatland. Peatlands are natural wetland ecosystems "where soils are peat -- the partially or incompletely decomposed remains of plants and, to some extent, animals" (Johnson 1985). Peatlands occur where there is high precipitation or low evapotranspiration, cool temperatures, short growing seasons, high acidity, and where hydrologic conditions favor water accumulation and retention over all or much of the growing season (Damman and French 1987). Peatlands occur throughout much of the world, but are most common in the northern parts of North America and Eurasia.

Decomposition in peatlands occurs very slowly due to low oxygen concentrations and cold temperatures (van Breemen 1995). Extreme acidity further reduces rates of decay in some peatlands (Johnson 1985). Consequently, nutrients tend to be sequestered in the undecayed peat and are largely unavailable to living plants.

Peatlands are classified based on their nutrient status and three classes are commonly described: minerotrophic, oligotrophic, and ombrotrophic. Minerotrophic peatlands are enriched with nutrients, usually from surface water or ground water influx, and are commonly known as fens. Oligotrophic peatlands receive nutrients from surface water, ground water, and precipitation but rates of influx are very low and thus these peatlands are rather infertile. Ombrotrophic peatlands receive nutrients exclusively from atmospheric precipitation and are the most sterile of the three types (Johnson 1985, Gorham and Janssens 1992, van Breemen 1995). The term bog is usually restricted to ombrotrophic peatlands and the more extreme oligotrophic peatlands (Johnson 1985). Bogs are more acidic than fens primarily due to the ability of *Sphagnum* mosses to acidify their immediate surroundings (Moore and Bellamy 1974, Crum 1988, Andreas and Bryan 1990, van Breemen 1995).

Kettlehole bogs, such as that at Spruce Hole, are peatlands that occur in deep depressions formed long ago during deglaciation. Massive blocks of ice broke off of the retreating ice front, were surrounded or buried by glacial sediments, and later melted, leaving behind "kettles" (Longwell, Flint and Sanders 1969, p. 274). These basins were colonized by aquatic and emergent plants and later by terrestrial plants that colonized the accumulating peat over the millennia.

1.3 Peatlands in the Northeast

Peatlands are not common in the northeastern U.S. and, thus, have been of special interest to ecologists and conservation biologists (Johnson 1985). Over the past two decades, a concerted effort has been made to inventory and classify peatlands of the northeast based primarily on their plant species composition (see Worley and Sullivan 1980, Worley 1981, Damman and French 1987). These studies agree that the lack of detailed information about specific peatlands has prevented the development of firm generalizations about patterns of community structure and diversity in these ecosystems.

In New Hampshire, several peatlands, including Spruce Hole Bog, have been identified as unique ecological areas due to the rarity of habitat, vegetation, or of plant and animal species (Lyon and Bormann 1962, Favour 1971, Lyon and Reiners 1971, Bayless 1981, Johnson 1985, Hellquist 1994, Sperduto and Ritter 1994, Sperduto 1995). To date, however, only a few have been studied intensively enough to allow comparison with Spruce Hole Bog (Dunlop 1983, 1987, Fahey 1993, Fahey and Crow 1995, Hellquist 1994).

Dunlop (1983, 1987) mapped and described five major plant community types at Mud Pond Bog, a peatland in Hillsborough, New Hampshire. Fahey (1993) carried out a similar project in Ossipee, New Hampshire. She used computer techniques to identify five major plant communities in Pequawket Bog and provided a flora for nearby Heath Pond Bog. Hellquist (1994) described the vascular plant communities of Mud Pond Bog in Moultonborough, New Hampshire, and then carefully compared the flora of his bog with those studied by Dunlop and Fahey. He found that all four New Hampshire peatlands were very similar in plant species composition.

None of the studies mentioned above included bryophytes (mosses and liverworts) a conspicuous omission as members of the genus *Sphagnum* -- the peat mosses -- form the bulk of the peat in many peatlands and are known to be important regulators of water level and chemistry and, thus, presence or absence of plant species (Vitt and Slack 1975, Crum 1988, Gorham and Janssens 1992).

PART II. REVIEW OF EXISTING INFORMATION ON SPRUCE HOLE

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Spruce Hole Bog has been recognized as a unique ecological area by the U.S. National Park Service and is a registered National Natural Landmark. The Natural Landmark evaluation report (Favour 1971) states that "Spruce Hole Bog has exceptional value in that it is an ecological community significantly illustrating the characteristics of a typical *Sphagnum*-Heath bog localized in a specialized geological setting, i.e., it is a true kettle-hole bog." The bog is cited as being the last of six kettlehole bogs in southern New Hampshire.

Dr. Albion Hodgdon collected vascular plants at Spruce Hole Bog from 1931 to 1969 and his voucher specimens are housed in the Hodgdon Herbarium at the University of New Hampshire. Hodgdon's (1962, 1971) research is the only published botanical work done at Spruce Hole Bog. His species list was incomplete but he provided some information on the past extent of vascular plant assemblages. An unpublished report (Femino 1969), apparently the result of a student research project at the University of New Hampshire, listed 37 species of phytoplankton (algae) found in the bog pond in 1969. Another unpublished student paper provided data on tree ring widths of black spruce growing in the bog (Cummings 1969).

Invertebrates of the bog have received some study. Studies by Dr. Donald S. Chandler of the University of New Hampshire have revealed a diverse insect fauna of over 1700 species (Chandler 1996). Of particular interest are the banded bog skimmer dragonfly (*Williamsonia lintneri*), a species endemic to New England, and the blundering *Stenus* rove beetle (*Stenus mendosus*), which is only found in Spruce Hole Bog and one other bog in Connecticut. According to Dr. Chandler, the banded bog skimmer dragonfly was last collected at Spruce Hole Bog in 1950, while the rove beetle is abundant and has been collected through the 1980's. The bog elfin butterfly (*Incisalia laneeoriensis*), which is a specialized feeder on young foliage of black spruce (Johnson 1985) was last collected at Spruce Hole in 1897 but still may be extant. Specimens of these insects are located in the University of New Hampshire insect collection. Dr. Chandler, Department of Zoology, should be consulted for more detail concerning these organisms. Two specialized studies of bog invertebrates have been conducted at Spruce Hole. Debboun (1983) studied mosquitoes and Donaldson- Fortier (1993) studied mites associated with peat mosses.

PART III. THE FLORA AND VEGETATION OF SPRUCE HOLE BOG

3.1 Introduction

This part of the report describes the methods used to characterize the flora and map the vegetation of Spruce Hole Bog. Results are then presented and compared to the flora and vegetation of other New Hampshire peatlands.

3.1.1 Flora Flora were determined by examining the bog twice a week from late March through October in 1993 and then approximately weekly during the growing season of 1994 to confirm and extend the findings. Nomenclature followed Gleason and Cronquist (1991) for vascular plants, Crum and Anderson (1981) for mosses, and Crum (1991) for liverworts. Herbarium specimens of all species were deposited in the Hodgdon Herbarium (NITA) at the University of New Hampshire.

3.1.2 Vegetation Sampling Plant distribution and abundance data were collected in July 1993 along thirteen parallel transects separated from each other by 10 meters. Each transect was divided into eight-meter segments and one plot (1 meter by 1 meter in size) was placed randomly within each segment. For each plot, the species present were identified and listed, as well as their abundances. Abundance was measured as 'percent cover': the percent of the plot covered (in vertical projection) by the foliage of the species, estimated to the nearest five percent. In all, there were 113 sample plots. For mapping purposes the location of each transect and distance of each plot along the transect were recorded.

3.1.3 Classification of Communities Sample plots were classified based on species composition and abundance using the computer program TWINSPAN (Two-Way Indicator Species Analysis [Hill 1979]). The plant associations and distributions were then interpreted based on the TWINSPAN output.

3.1.4 Surveying and Vegetation Mapping The bog perimeter was surveyed by sighting and recording distances and angles to landmarks along the border between the *Sphagnum* mosses in the lagg (moat) and the surrounding forest. A compass and SONIN 150 ultrasonic distance meter were used to make these measurements. From these data a computer map of the bog was constructed on which the distribution of the plant communities was plotted based on sample plot locations and their classification. The appropriateness of the community boundaries on the map was checked in the field.

3.1.5 Basin Profile Data were collected for the basin profile by pushing an extendible metal probe into the peat until it reached solid ground. This was done at approximately 5 meter increments along two perpendicular transects. Depth to the surface of the accumulated peat in the center of the pond was measured by dropping a plumb bob on a string until it hit peat and then measuring the length of string that was submerged.

3.1.6 pH Measurement pH was measured within each of the designated plant communities in 1994 on the following dates: May 12; June 4, 18, 29; July 10: August 1 and 5. No community was sampled less than four times. Sampling involved pushing a 500 ml plastic bottle into the peat until it filled with water, then analyzing the contents using a BECKMAN Φ20 Series pH meter (Beckman Instruments, Inc. Fullerton C.A.) within two hours of sampling.

3.2 Results and Discussion

3.2.1 Dimensions of the Bog Spruce Hole Bog is rough1y oval in shape, approximately 152 m long, 80 m wide, and one hectare in area (Figure 1). A basin profile appears in Figure 2. Depth to peat in the center of the pond was 5.5 m. Depth to mineral substrate (sand and gravel) remains undetermined in the deepest portions as it exceeded the length of the probe (14m).

3.2.2 Flora In the following discussion of the flora of Spruce Hole Bog, common names will be used where they are available. Scientific names appear with common names in

Table 1. Many sedges, mosses, and liverworts have no widely used common names and, consequently, only scientific names will be used for these plants.

Fifty-three plant species representing 24 families were found in Spruce Hole Bog. Thirty-seven of these species were vascular plants: flowering plants, conifers, and ferns (Table 1). Sixteen were mosses and liverworts (bryophytes) (Table 2). Among the vascular plants, the heath and sedge families had the greatest number of species. Among the mosses and liverworts, peat mosses (the genus *Sphagnum*) were the most species-rich.

Many New Hampshire peatlands contain species that are endangered, threatened, or of "special concern" according to New Hampshire's Natural Heritage Inventory, Department of Resources and Economic Development (DRED 1995). Of these species only grass pink (*Calopogon tuberosus*) and pitcher plant (*Sarracenia purpurea*) have been documented at Spruce Hole Bog and both species are listed as being of "special concern." Hodgdon (1962, 1971) collected grass pink prior to 1960, but it could not be found during the field seasons of 1993-95. It should be noted, however, that some bog orchids, such as grass pink, flower intermittently, even where they are abundant (Johnson 1985). Pitcher plant was abundant at Spruce Hole Bog and did not appear to be declining (DRED 1995).

3.2.3 Indicator Species Species found at Spruce Hole Bog that have been cited as indicators of nutrient-poor (oligotrophic or ombrotrophic) peatlands included black spruce, cotton-grasses, leatherleaf, sundew, false Solomon's seal, and some peat mosses (Jeglum 1971, Worley 1981, Johnson 1985). Some minerotrophic (slightly nutrient-enriched) indicator species also occurred, including cranberry, winterberry and a sedge, *Carex canescens* (Jeglum 1971, Worley 1981). Most of these species were typically found in or near the lagg (moat) or pond where peat conditions were less acidic (Table 3). The large number of oligotrophic/ombrotrophic indicator species and the low pH values suggested that Spruce Hole Bog is very infertile and acidic.

3.2.4 Vegetation Based on the presence and abundance of plant species in 113 meter-square plots, the computer program TWINSPAN identified five communities: (1) the lagg (moat) community, (2) the low shrub community (3) the *Sphagnum*/sedge lawn, (4) the tall shrub community, and (5) the bog forest community (Figure 4). The lagg community was divided into three phases: (1) the leatherleaf /water-willow phase (2) the cotton-grass phase and (3) the *Carex* phase.

The five communities can be aligned along a gradient of decreasing soil moisture as follows: lagg community, low shrub, *Sphagnum/*sedge lawn, tall shrub, and bog forest. Peat was least consolidated and the peat surface closest to the water table in the lagg community, while in the bog forest peat was well consolidated and slightly raised above the water table.

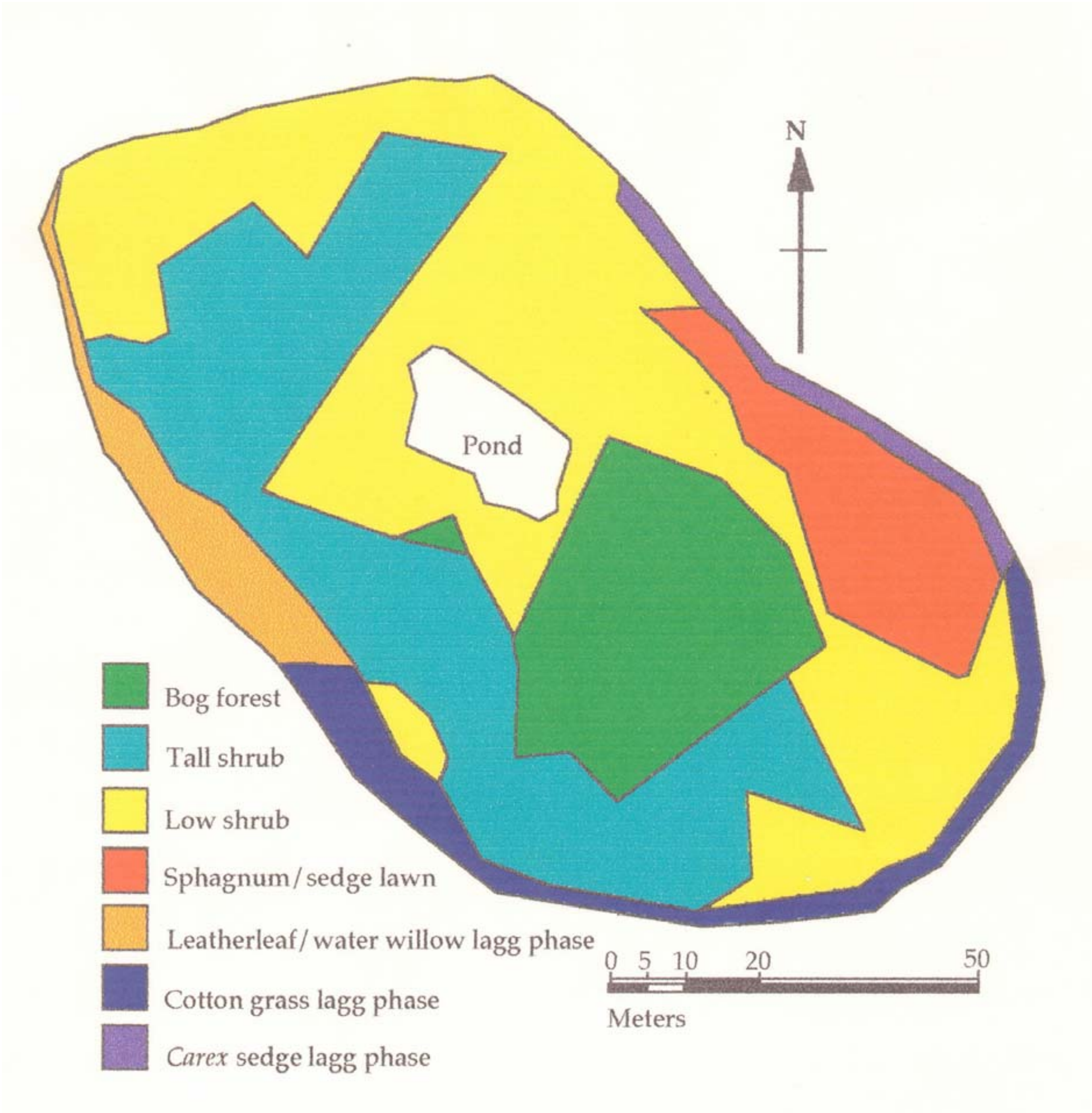

Figure 1. Vegetation map of Spruce Hole Bog. The five communities and three phases of the lagg community were delineated by mapping plots classified by the program TWINSPAN based on species composition and abundance.

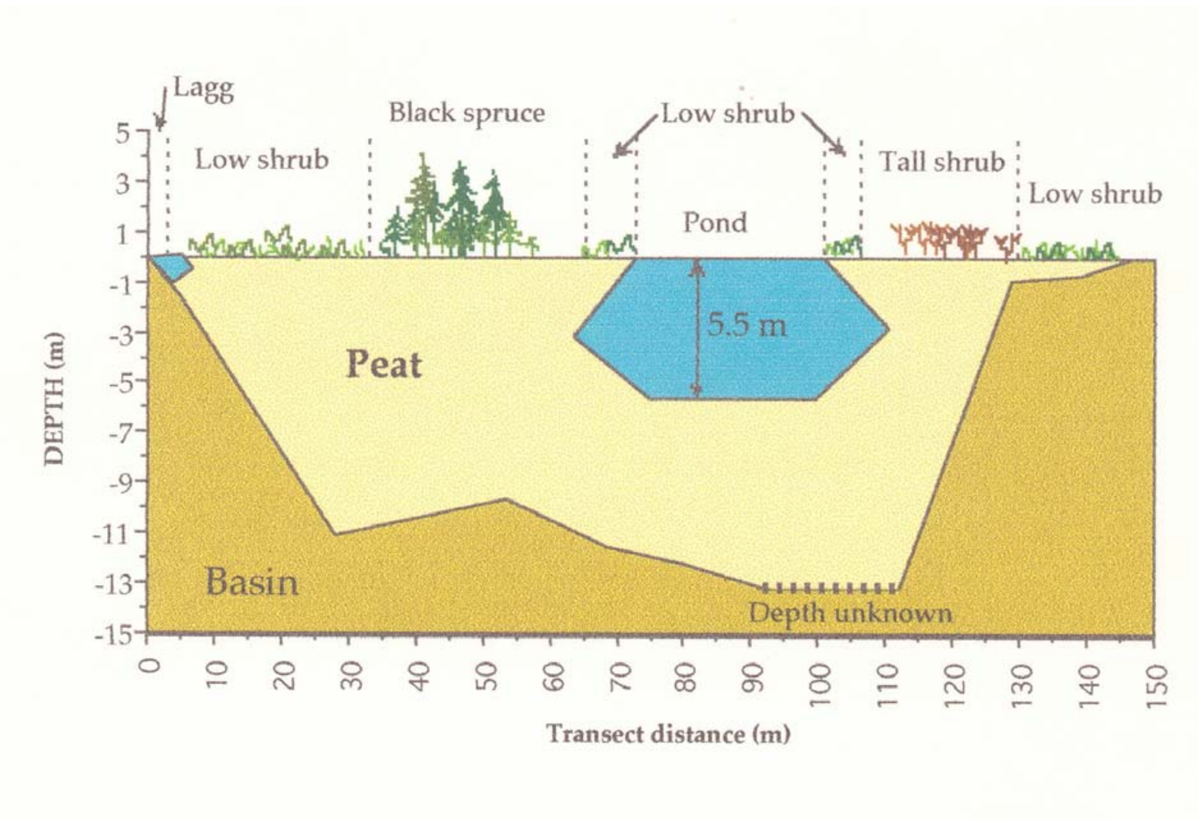

Figure 2. Basin profile of Spruce Hole Bog along a southeast to northwest transect. Depth to mineral substrate in the deepest portion of the basin is unknown.

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Table 1. Vascular plant flora of Spruce Hole Bog. Mean percent cover and frequency (%of plots in which the species occurs) are listed for those species that were included in the TWINSPAN analysis. Those species without abundance measures ere infrequent and did not occur in the sample plots. Listing of families follows Gleason and Cronquist (1991).

Common name	Scientific name	%Cover	% Frequency
ROYAL FERN FAMILY			
Cinnamon fern	*Osmunda cinnamomea* L.	3	19
PINE FAMILY			
Black spruce	*Picea mariana* (Miller) BSP	4	13
White pine	*Pinus Strobus* L.		
BIRCH FAMILY			
Black birch	*Betula lenta* L.	<1	<1
Gray birch	*Betula populifolia* Marshall	<1	<1
PITCHER PLANT FAMILY			
Pitcher plant	*Sarracenia purpurea* L.	<1	13
SUNDEW FAMILY			
Round-leaved sundew	*Drosera rotundifolia L.*	<1	39
HEATH FAMILY			
Male-berry	*Lyonia ligustrina* (L.) DC.	2	27
Black huckleberry	*Gaylussacia baccata* (Wangenh.) K. Koch.	4	21
Sheep laurel	*Kalmia angustifolia* L.	4	42
Bog laurel	*Kalmia polifolia* Wangenh.	<1	2
Leatherleaf	*Chamaedaphne calyculata* (L.) Moench.	14	52
Lowbush blueberry	*Vaccinium angustifolium* Aiton		
Highbush blueberry	*Vaccinium corymbosum* L.	20	58
Cranberry	*Vaccinium macrocarpon* Aiton	<1	4
Small cranberry	*Vaccinium oxycoccos* L.	<1	6
Creeping snowberry	*Gaultheria hispidula (*L.) Muhl.		
Wintergreen	*Gaultheria procumbens* L.		
Rhodora	*Rhododendron Canadense* (L.) Torr.		
PRIMROSE FAMILY			
Starflower	*Trientalis borealis* Raf.		
ROSE FANIILY			
Black chokeberry	*Aronia melanocarpa* (Michx.) Elliott	1	27
Shadbush	*Amelanchier canadensis* (L.) Medikus		
LOOSESTRIFE FAMILY			
Water-willow	*Decodon verticillatus* (L.) Elliot	13	35
HOLLY FAMILY			
Mountain holly	*Nemopanthus mucronatus (L.) Trel.*	2	6
Smooth winterberrv	*Ivex laevigata* (Pursh) Gray	<1	2
Winterberry	*Ilex verticillata* (L.)Gray	<1	8
MAPLE FAMILY			
Red maple	*Acer rubrum* L.	<1	28

Table 1. (Continued)

Common name	Scientific name	%Cover	% Frequency
CASHEW FAMILY			
Poison sumac	*Toxicodendron vernix* (L.) Kuntze	<1	9
BLADDERWORT FAMILY			
Bladderwort	*Utricularia geminiscapa* Benj.	<1	3
HONEYSUCKLE FAMILY			
Withe-rod	*Viburnum nudum* L. var. cassinoides T.&G.		
SEDGE FAMILY			
Conifer cotton-grass	*Eriophorum tenellum* Nutt.	1	20
Tussock cotton-grass	*Eriophorum vaginatun* L. var. *spissum* (Fern.)B. Boivin	<1	5
Tawny cotton-grass	*Eriophorum virginicum* L.		
Sedge	*Carex canescens* L.	2	7
Three-seeded sedge	*Carex trisperma* Dewey var. *billingsii* Knight	2	12
Beak-rush	*Rhynchospora alba* (L.) Vahl.	1	2
LILY FAMILY			
False Solomon's seal	*Smilacina Trifolia* (L.) Desf.	<1	2

In the following discussion the Spruce Hole plant communities will be described in order of increasing 'dryness' of the substrate. Comparison with communities of other peatlands in the region will be made. It should be kept in mind, however, that community types are quite variable from bog to bog and that the amount of detailed literature available for comparison is small compared to the estimated hundreds of peatlands in the northeast.

3.2.5 The lagg community Computer analysis identified a distinct plant community located in the lagg or moat of the bog. The lagg was located between the upland forest and the bog mat, where water was present during most of the growing season but no mat of consolidated peat formed (Figure 1). The lagg vegetation and peat were not cohesive and would not support the weight of a person. The lagg community was dominated by one species of peat moss, *Sphagnum cuspidatum,* and had three phases: (1) the leatherleaf/water-willow phase (2) the cotton-grass phase, and (3) the *Carex* phase. Each phase was named according to the plant species co-dominating with *S. cuspidatum* (Table 4). The *Carex* lagg phase occurred in a narrow band along the northeast margin of the bog and was densely mantled with a sedge, *Carex canescens.* The leatherleaf/water-willow phase was very similar to the low shrub community in the northern reaches of the bog. The peat substrate, however, was not solid here and *Sphagnum cuspidatum* rather than *S. recurvum* dominated. The cotton-grass phase of the lagg community occupied a thin band, no more than five meters wide, around the southern end of the bog.

Table 2. Bryophyte flora of Spruce Hole Bog. Mean percent cover and frequency (% of plots in which the species occurs) are listed for those species that were included in the TWINSPAN

analysis. Those species without abundance measures were infrequent and did not occur in the sample plots.

Family	Scientific name	% Cover	% Frequency
Aulacomniaceae	*Aulacomnium palustre* (Hedw.) Schwaegr.	<1	8
Dicranaceae	*Diranum flagellare* Hedw.		
	Diranum ontariense Peters		
	Diranum polysetum Sw.		
	Diranum scoparium Hedw.		
Hylocomiaceae	*Pleurozium schreberi* (Brid.) Mitt.		
Sphagnaceae	*Sphagnum cuspidatum* Erh. ev Hoffm,	10	14
	Sphagnum recurvum P. -Beauv.	41	80
	Sphagnum capillifolium (Erh.) Hedw. var. *tenellum* (Schimp.) Crum	<1	20
	Sphagnum fuscum (Schimp.) Klinggr.	<1	4
	Sphagnum magellanicum Brid.	39	76
	Sphagnum fimbriatum Wils. *ex* Wils. & J.D. Hook		
Amblystegiaceae	*Warnstorfia fluitans* (Hedw.) Loeske*		
Calypogejaceae	*Calypogeja mulleriana* (Schiffn.) K. Mull.		
Cephaloziaceae	*Cephalozia plenicaps* (Aust.) Lindb.		
Ptilidiaceae	*Ptilidium pulcherrinum* (Web.) Hampe		

* *Warnstorfia fluitans* (Hedw.) Loeske = *Drepanocladus fluitans* (Hedw,) Warnst. The taxonomy for this species was updated using Anderson et al. (1990) rather than Crum and Anderson (1981).

Table 3. Mean pH values of water in the peat of each plant community at Spruce Hole Bog. Standard deviations (sd) and sample sizes (n) appear in parentheses. Data collected during the summer of 1994.

Community	pH
Bog forest	3.63 (sd = 0.21, n = 4)
Tall shrub	3.67 (sd = 0.16, n = 4)
Low shrub	3.85 (sd = 0.20, n = 7)
Sphagnum/sedge lawn	3.91 (sd = 0.33, n = 7)
Lagg	4.26 (sd = 0.50, n = 4)

Table 4. Mean percent cover for dominant species (>5% in at least one community) within each plant community at Spruce Hole Bog.

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Plant community

Taxonomy	Cotton grass lagg phase	Leatherleaf-water willow lagg phase	*Carex* lagg phase	Low shrub	Sphagnum/sedge lawn	Tall shrub	Bog forest
Cinnamon fern			8			6	3
Black huckleberry				2		7	9
Highbush blueberry		1	24	7	3	30	41
Three-seeded sedge							9
Mountain holly						2	8
Black spruce							23
Sheep laurel				1		10	4
Sphagnum magellanicum			6	42	6	48	64
Cotton-grass	15			1	9	1	
Water-willow		38	34	24		5	
Sphagnum recurvum	15	22	3	46	93	47	17
Leatherleaf		40	1	27	28	4	
Male-berry	3	2		3	6	2	
Sphagnum cuspidatum	84	78	86	1			
Carex canescens			37		3		

In most bogs, the lagg habitat experiences fluctuating water levels (Buell and Buell 1975), nutrient input from runoff, and higher decay rates during drought or dry periods later in the growing season (Damman and French 1987). Consequently, nutrient levels and Ph values are higher in the lagg than in other bog habitats. At Spruce Hole the lagg was less acidic than the other communities (Table 3).

3.2.6 The low shrub community was uniformly dominated by leatherleaf and water willow (Table 4). Moss cover was composed primarily of *Sphagnum recurvum* and *S. magellanicum*. Subsidiary species included cranberry, male-berry, huckleberry, and round-leaf sundew, but these species only seemed to occupy the sparse drier patches on the edge of the community where it gave way to the tall shrub community. Plants seldom reached heights of over 50 cm in this community. The peat was very wet and hardly stable enough to support the weight of a person. The mat here was least consolidated of all the plant communities except those in the lagg.

Dunlop (1983) reported a leatherleaf-water willow community adjacent to the open water at Mud Pond Bog in Hillsborough. Water willow was not a conspicuously dominant plant at Pequawket bog in Ossipee, however, although it could be found at low percent cover (Fahey 1993).

3.2.7 The *Sphagnum*/sedge lawn community was a small, homogeneous community with plants no more than 50 cm tall, growing on consolidated peat in the eastern part of the bog between the lagg and the black spruce muskeg (Figure 1). Shrub cover was low, and uniform mats of *Sphagnum* mosses with scattered sedges were obvious among the dwarf shrubs. The community was dominated by *Sphagnum recurvum* and leatherleaf (Table 4). Other plants included cotton-grasses, male-berry, a sedge (*Carex canescens*) large-leaf cranberry, and chokeberry.

The *Sphagnum*/sedge lawn community at Spruce Hole Bog was similar to the *Sphagnum capillifolium*-leatherleaf community described as one of five dwarf shrub communities in northeastern peatlands by Dammam and French (1987). Such *Sphagnum* lawns often have many co-dominant species according to Worley (1981). The leatherleaf community at Mud Pond Bog in Hillsborough (Dunlop 1983) is a similar *Sphagnum* lawn community although it is dominated by beak rush and three-seeded sedge rather than cotton-grasses. Sheep laurel was more prominent at Mud Pond Bog (Hillsborough) than at Spruce Hole in this community type.

3.2.8 The tall shrub community surrounded the open pond and extended into the northern reaches of the peatland (Figure 1). Hummock and hollow development was most pronounced in this community, and the dominant vascular plant species was highbush blueberry, with approximately 30% cover and typically about two meters tall. Shorter black huckleberry was also abundant, especially where the tall shrubs gave way to a more open *Sphagnum* mat. Stems of both species were associated with hummocks of *Sphagnum recurvum* and *S. magellanicum* (Table 4). *Sphagnum recurvum* was common in the wet troughs. Small, concentrated patches of *Smilacina trifolia* were found growing between hummocks in the wetter parts of the community that were open to direct sunlight.

Dunlop (1983) identified a huckleberry-highbush blueberry cover type at Mud Pond Bog (Hillsborough), which was very similar to the tall shrub community at Spruce Hole Bog. Highbush blueberry, huckleberry, and sheep laurel were common shrubs in both communities. Damman and French (1987) list tall shrub thickets dominated by highbush blueberry as common in bogs of southern New, England.

Approximately 25 standing dead snags of white pine, approximately 10-35 cm dbh (dbh = diameter at breast height, 1.3 m above the ground) were found in this community. Some large, cut stumps 20-35 cm in diameter were also evident on the bog mat, indicating that some trees had been harvested. A few stems of live white pine were found in this community, but all were less than two meters tall and had sparse and yellow-green foliage.

The peat in this community tended to be anchored and did not "quake" when walked on. The pines may have found this substrate amenable to colonization in the past, perhaps because the solid texture of the accumulated peat was drier during an extended period of low water.

3.2.9 The bog forest community was the most distinctive community type in the bog, consisting of a dense, nearly closed stand of black spruce (Figure 1). The canopy of this forest was continuous but did not exceed four meters in height. Black spruce stems did not exceed 10 cm dbh. Tall shrubs such as highbush blueberry, black huckleberry, and mountain holly were common (Table 4) especially around the forest margin. Herbaceous cover was scant and consisted mostly of three-seeded sedge and creeping snowberry. There was a diverse bryophyte flora with a variety of fork mosses (Dicranaceae) and liverworts scattered among hummocks of *Sphagnum recurvum* and *S. magellanicum*. Many of these mosses and liverworts were not found elsewhere in the bog.

Damman and French (1987) listed two types of bog forest community found in northeastern bogs: the *Sphagnum magellanicum*/black spruce type and the three-seeded sedge/black spruce type. The S. *magellanicum*/black spruce forest is commonly found on oligotrophic peat in raised peatlands in northern New Hampshire and Maine. The three-seeded sedge-black spruce forest community type is common on peatland borders in both boreal and hardwood (southern) forest zones. The black spruce community at Spruce Hole has affinities to both of these types. In terms of its physical structure and location in the bog it is more similar to the *Sphagnum magellanicum*/black spruce type, but its species composition more closely resembles the three-seeded sedge/black spruce community. Similar black spruce stands do not occur at any of the four New Hampshire peatlands that have been studied quantitatively (Dunlop 1984, Fahey 1993, Hellquist 1994), thus, closed black spruce stands are probably uncommon in southern New Hampshire.

3.2.10 <u>Classification</u> The basin morphology, hydrological conditions, and lack of extensive areas of raised peat (peat elevated well above the water table) qualify Spruce Hole Bog as a primary, or level, peatland (Moore and Bellamy 1974, Johnson 1985). However, the high acidity (pH < 4.2), low species richness (Table 5), and preponderance of *Sphagnum* and other oligotrophic/ombrotrophic indicator species justifies classification of Spruce Hole as a bog rather than a fen (Johnson 1985, p. 28). Thus, the peatland at Spruce Hole is a 'level bog', typical of very oligotrophic peatlands in southern New Hampshire and Vermont, and southern New England.

Spruce Hole Bog is similar to other New Hampshire peatlands that have been intensively studied. This is true both in terms of floristic composition and vegetation. The flora of Spruce Hole is small, however, and is typically a subset of the flora of other peatlands. Specifically, Spruce Hole contains less than half of the species found in any of the four quantitatively studied New Hampshire peatlands (Table 5), and every plant species found there also occurs in at least one of the other four bogs.

Table 5. Number of vascular plant species found in selected New Hampshire peatlands.

Mud Pond Bog (Moultonborough)[1]	124
Pequawket Bog (Ossipee)[3]	109
Mud Pond Bog (Hillsborough)[2]	101
Heath Pond Bog (Ossipee)[3]	70
Spruce Hole Bog (Durham)	37

[1] Hellquist 1994, [2] Dunlop 1983, [3] Fahey 1993

The low species richness at Spruce Hole may be due to a number of factors, among which are its extreme acidity and oligotrophy, its small size, its uniform physical setting, and its great distance from other peatlands. Spruce Hole Bog, judging by the pH measurements and indicator species that occur there, is more oligotrophic than any similar New Hampshire peatland in the literature. It is also the smallest in size (the other four peatlands are at least 10 times the area of Spruce Hole), and it lacks the environmental heterogeneity found in other peatlands in which stream channels, large ponds, and eccentrically configured basins create different habitats, which support different species and communities. The lack of any floating-leaved aquatic assemblage as occurs at Mud Pond Bog (Hillsborough) and Pequawket Bog, for instance, is most likely due to a lack of suitable microhabitat. There are also few peatlands in close proximity to Spruce Hole to provide sources of new species. Pequawket and Heath Pond Bogs, in contrast, have numerous bogs and fens nearby from which plants may readily disperse.

Four of the five plant communities described at Spruce Hole are similar to those of other southern New Hampshire peatlands, varying only slightly in terms of species composition. Communities similar to the black spruce stand at Spruce Hole, however, have not been reported from southern New Hampshire, though they may occur in unstudied peatlands there. Damman and French (1987) report similar conifer forest assemblages in more northern regions of the state, and similar communities can be found at Arcadia Bog in Massachusetts (Motzkin and Patterson (1991) and Victory Basin Bog in Vermont (Bubier 1991). In other New Hampshire peatlands black spruce tends to occur as scattered trees (Dunlop 1983, Fahey 1993, Hellquist 1994).

PART IV. RECENT BOG HISTORY: DYNAMICS Of WHITE PINE

4.1 Introduction

During the vegetational analysis it became apparent that while white pine was a minor component of the bog community at present, it had been more abundant at Spruce Hole a few decades ago. At the time we sampled the bog there was an abundance of large, dead, white pine snags on the mat of the bog as well as around the bog perimeter. When the dead pines on the bog mat were alive and had branches and foliage, parts of the bog would have been covered by a nearly continuous pine canopy. The lack of any living white pine greater than two meters tall today suggests that the white pine population has declined greatly and that past environmental conditions must have been very different.

Any baseline investigation of a natural community should consider the dynamics of the system and the dead white pine stems provided an opportunity for us to assess the magnitude and rate of recent change in the plant community at Spruce Hole. Such information may be useful in gauging the significance of future changes in the bog community. To determine the rate and magnitude of change in white pine abundance in the bog, the following were performed: (1) reconstructed the past distribution of the white pine population on the bog mat by mapping the locations of stumps and fallen and standing snags; (2) described the present distribution of white pine in the bog by mapping all live pine stems, (3) used tree ring analysis to date the mortality of pine stems on the bog mat and around the margin of the bog.

4.2 Methods

The distribution of all live and dead white pine on the mat of the bog were mapped. Locations of dead pines were established using a compass and SONIN 150 ultrasonic distance-meter. The present and past distribution of white pine was then superimposed on a map of the present vegetation in order to infer the former extent of the pine population in relation to current plant communities.

Two or more increment cores were taken from dead trees in two areas: (1) the bog mat, mainly in the tall shrub, bog forest, and low shrub communities; and (2) at the perimeter of the bog, both in the moat and at the border between the moat and adjacent upland. Cores were taken from 16 trees on the mat and 10 at the bog perimeter, all greater than 10 cm dbh. In addition, cores were taken from 13 mature, living, upland trees. Increment cores are small cylinders of wood, approximately 4 mm in diameter, that are extracted radially from the tree. The cores were dried, mounted on wood blocks, and sanded to a fine polish until individual cells could be seen when viewed under a dissecting microscope. Tree rings were measured to the nearest micrometer and analyzed using standard dendrochronological techniques (Fritts 1976, Schweingruber 1988).

Growth patterns in tree rings are similar across many trees in a habitat. It is thus possible to date rings from a dead piece of wood in which the last year of growth is unknown by comparing the patterns of growth with wood samples for which absolute dates of ring production are known. This process is known as crossdating (Wigley et al. 1987). Cores from the live upland pine trees were used to establish a master chronology in which average ring widths were known for each year. Tree ring widths from the dead trees were then compared, where the relation between ring width and year was not known, to the master chronology. Crossdating each of the dead stems allowed identification of the year in which its mortality occurred. Crossdating was accomplished using the program COFECHA (Holmes 1983).

4.3 Results

Over 80 dead white pine stems were mapped on the bog mat. Over 30 of these exceeded 20 cm dbh (about 8 inches) and some approached 40 cm dbh. The distribution of dead pine stems (Figure 3) suggested that a white pine population once extended in a ring around the pond following what is today (and probably was then) the most consolidated areas of peat. The distribution of these dead trees corresponded well to the distribution of the tall shrub community, the fringes of the bog forest, and the relatively more consolidated portions of the *Sphagnum*/sedge lawn (Figure 3). The population of live, white pine, in contrast, was

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restricted to two small areas in the tall shrub and bog forest communities (Figure 4) and consisted entirely of seedlings and saplings, none of which exceeded three meters in height or 10 cm dbh.

Crossdating of the dead trees was successful, allowing estimation of the year of death for each tree. White pine trees growing on the peat mat of the bog died between 1939 and 1962 (Figure 5a,b). The mortality of trees at or near the bog perimeter began in 1967 but occurred mostly in the late 1980s and early 1990s (Figure .5b). 'The two perimeter trees that died first (1967 and 1982) were situated farther from the upland border (in deeper water) than those trees dying after 1985.

Tree growth, measured as the increase in cross-sectional wood area per year, was plotted over time for each tree from the mat, perimeter, and upland (Figure5a). In trees from the bog mat, a sharp decline in growth beginning in 1948 just preceded the period of greatest mortality in the 1950s ('A' in Figure 5a). All 13 perimeter trees showed greatly reduced growth in 1982-83 ('D' in Figure 5a), although most individuals regained high growth rates ('F' in Figure 5a) before dying in the late 80s or early 90s. Growth of upland trees, alive in 1995 when they were cored, showed very low values in the late 1940s and early 1980s ('F' in Figure 5a), corresponding to periods of reduced growth in the dead trees from the mat and perimeter.

4.4 Discussion

White pine often occurs in peatlands along with other conifers such as black spruce and larch (Johnson 1985). Due to the low oxygen levels and other stresses, however, white pine often fails to reach reproductive maturity in peatlands and most newly established trees are probably the result of seeds transported from outside the community to favorable sites on the peat surface.

Dead snags of white pine are often found in wetlands where establishment and rapid growth of pine during time of low water levels is followed by flooding and consequent oxygen deprivation of roots for an extended period. Such flooding occurs commonly in marshes and fens after damming of streams by humans or beavers (e.g., Schwintzer and Williams 1974, Schwintzer 1979, Mitchell and Niering 1993). White pine mortality is less easy to explain in kettlehole peatlands, such as Spruce Hole, which have no inlet or outlet and typically receive water only from precipitation, runoff, or ground water.

It is evident that white pine has declined in abundance at Spruce Hole Bog in the last fifty years and several lines of evidence point to rising water levels as a likely cause. First, the present conditions in the bog appear to be poor for white pine growth and establishment. The few living pines in the bog exhibit symptoms (sparse foliage and chlorosis) typical of plants whose roots suffer from oxygen deprivation. Second, the area of the bog in which pines can establish appears to have contracted, with establishment occurring in communities with more consolidated peat (Figure 4). Third, the sequence of mortality, with trees on the mat dying first, followed by margin trees in the deeper water of the moat, and then by those nearer the upland is what one would expect where rising water levels are responsible. Fourth, the butts of many of the dead margin trees were covered by water most of the year. It is highly unlikely that white pine could establish at these sites today.

In addition to white pine, black spruce and red maple may also have declined in recent decades. Hodgdon's (1962) report states that the black spruce formed an "irregular and interrupted fringing border" around the pond in the center of the bog. At present, small (< 2 m tall) dead black spruce stems can be found around the pond, mostly on the south perimeter, but very few live trees exist outside of the bog forest community south of the pond (Figure 1). There are numerous dead red maple stems throughout the bog, some 4-5 meters tall, but very few live ones (S. Miller and T. Lee, personal observation). Tree ring analysis was not used to age mortality of red maple, as tree rings are difficult to discern in this species. The relative numbers and sizes of dead and live maples suggest, however, that the species has declined in recent years. Hodgdon (1962) also noted a declining maple population and implied that rising water levels were responsible. Cummings (1969), in a paper resulting from a student research project at UNH, suggested that rising water levels had reduced populations of both white pine and black spruce at Spruce Hole.

Several alternative hypotheses may be offered to explain the decline of white pine at Spruce Hole. Such hypotheses must take into account the local nature of the decline. While white pine has declined in the bog, it grows vigorously on the slopes surrounding the bog and throughout the adjacent upland. Thus, regional factors such as changes in temperature or growing season length are unlikely explanations. Insects and disease can cause local tree decline. There were gypsy moth outbreaks in Durham in 1946 and 1981, and these coincide with periods of reduced tree growth in the bog mat, perimeter, and upland trees that we cored. While red oak is the preferred forage of gypsy moths, these herbivores will switch to other species, including white pine, when preferred forage is depleted. Review of air photos taken in 1981 indicates a high level of defoliation in the vicinity of Spruce Hole. Air photos were unavailable for 1946. It is possible that the gypsy moth caterpillars defoliated the bog pines to such an extent that high mortality ensued. It is also possible that insect damage interacted with water stress; a gypsy moth outbreak could have exacerbated the deleterious effects of gradual flooding and could have started a general decline in forest growth that culminated in high mortality. Another alternative to rising water levels is deposition of pollutants, especially sulfur and nitrogen oxides, which could affect chemistry of the poorly buffered bog water more than that of the upland soils. Most of the evidence, however, points to rising water as the cause of tree decline at Spruce Hole.

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Figure 3. Distribution of dead white pine trees in relation to present plant communities. Stem diameter values in cm.

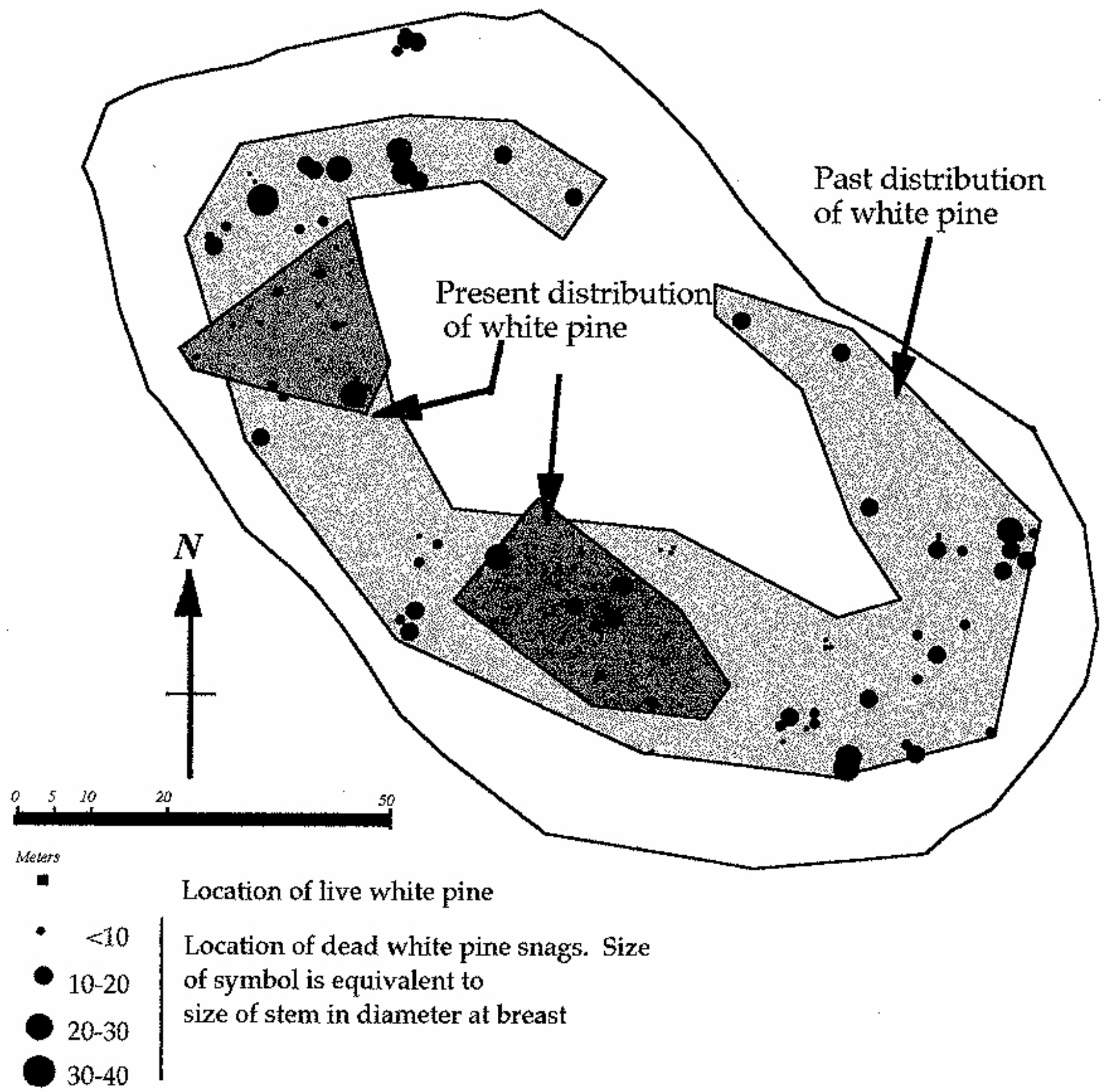

Figure 4. Past and present distribution of white pine at Spruce Hole Bog.

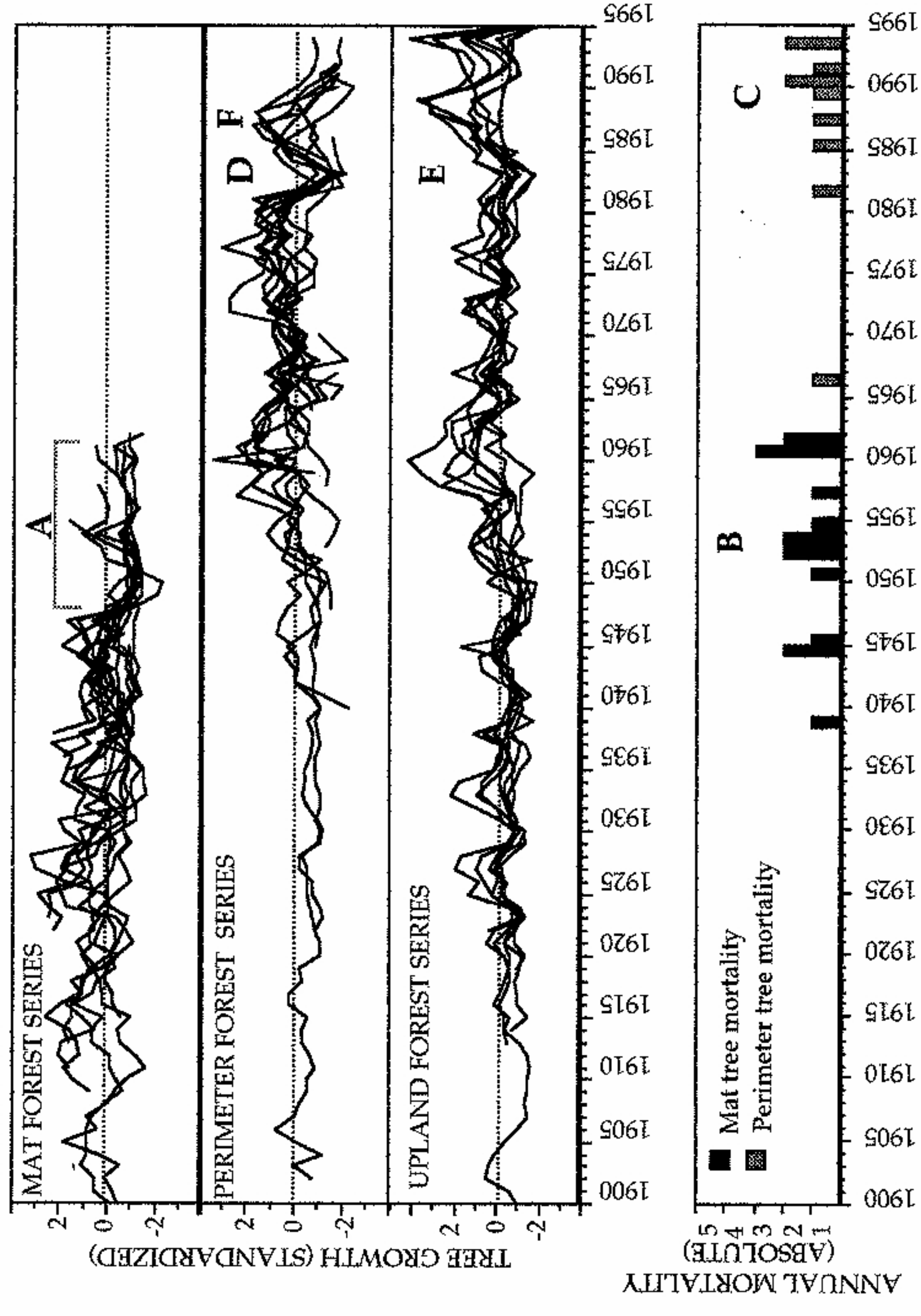

Figure 5a (top). Tree growth (standardized basal area increments) per year for each tree from the bog mat, bog perimeter, and upland forest. Figure 5b (bottom). Absolute annual mortality (number of trees dying per year) versus time for the mat and perimeter habitats.

If rising water level is the cause of tree decline at Spruce Hole, the next question to answer is: what is the cause of rising water levels? An obvious answer is increased levels of precipitation, but climate records for Durham show no such pattern. Both Hodgdon (1962) and Cummings (1969) suggested that logging of large pines in the bog prior to 1960 caused the Spruce Hole water table to rise, presumably due to reduced transpiration. Conifer forests can transpire more water than comparable deciduous forests or shrub vegetation (Bosch and Hewlett 1982); thus tree removal would result in a higher water table. Logging occurred in the uplands west and south the bog in the late 1980's and could be responsible for continued water level increases. Water table rise may also be due to the natural development of an impermeable layer of organic material beneath the bog surface (see hydrology portion of this report).

Tree mortality and the apparent loss of at least one orchid species, grass pink (see section on Flora and Vegetation), over the past 50 years indicate that vegetation change does occur at Spruce Hole. Thus, present communities should not be viewed as static associations, but rather as entities subject to the vagaries of environmental cycles, hydrological changes, disturbance, or autogenic community dynamics.

PART V. PERMANENT PLOTS

5.1 Purpose

Permanent monitoring plots were installed to allow quantitative assessment of future changes in species composition and abundance in the bog,

5.2 Location of plots

Three permanent plots were located in each of three plant communities: tall shrub, low shrub, and bog forest. In the lagg community peat was too unstable to permit establishment of permanent plots without seriously damaging the area being studied. The *Sphagnum*/sedge lawn community was too small to allow establishment of permanent plots. Permanent plots were located (and can be relocated) using compass bearings from reference tree trunks on the mat of the bog

5.3 Plot description

Each permanent plot (1.5 m X 4.0 m) was marked by two oak stakes (Figure 6). Stapled to the top of each stake was an aluminum tag bearing the plot number. The stakes were 1.5 m apart oriented along an east-west azimuth. Each stake marked the midpoint of one of the two long (4.0 m) sides of the plot. The long axis of the plot was oriented north-south. The stakes were used to locate two subplots (1.5 m X 2.0 m) and to anchor the subplot frame (Figure 6). The two subplots were designated as "north" or "south."

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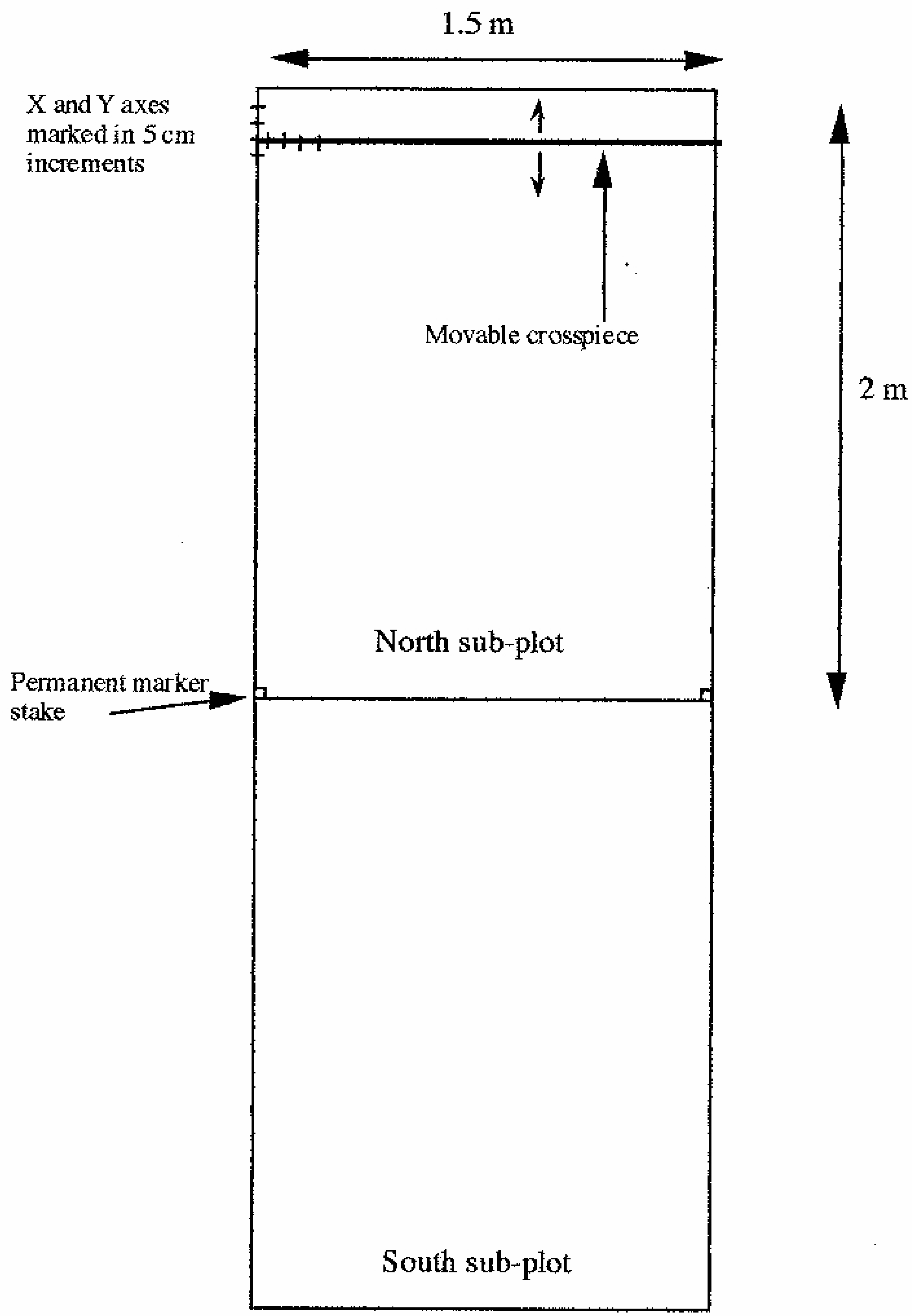

Figure 6. Diagram of permanent plot design.

Each subplot was sampled using a rectangular frame made from 0.5 inch diameter PVC pipe. The two longest sides (2.0 m) of the frame as well as a movable crosspiece were marked at 5 cm increments in order to create an X-Y coordinate system for sampling. The movable crosspiece could be adjusted vertically (Y - axis) using the increment markings on the sides of the subplot frame, and then sampling points could be located horizontally (X - axis) using the increment markings on the crosspiece.

5.4 Cover data collection

The origin of each sub-plot was located in the northeast corner of the sub-plot. The point-intercept method was used to quantify plant cover in each plot. Eighty points were sampled in each subplot by sampling 10 lines, each parallel to the Y axis. Eight points were examined per line. This method yielded a total of 160 sample points per plot. Lines were sampled beginning with 10 cm on the Y-axis and every 20 cm afterward (10 cm, 30 cm, 50 can ... etc ... 190 cm). X-axis points were designated along the crosspiece beginning at 5 cm and progressing in 20 cm intervals (5 cm, 25 cm, 45 cm ... etc ... 145 cm).

A point was sampled by placing a 30 cm piece of stiff wire (1 mm diameter) vertically against the X-axis crosspiece at the appropriate distance from the plot frame and recording one "tick" for each species of plant against which it came into contact. If one plant overtopped another a tick was assigned to both plants, and thus the total number of ticks per sub-plot often exceeded 80. Ticks for tall vegetation were approximate because the wire was not long enough to accurately contact tall vegetation. Percent cover was determined for each species in each subplot by dividing the number of ticks for that species by 80. A complete species list for each subplot was made to include species that may have been present, but were too rare to be sampled by the point-intercept technique.

Lastly, the number of stems of each woody shrub species and their estimated heights were recorded as either 1-2 meters tall or 2+ meters tall. Trunks of *P. mariana*, however, were mapped to the nearest centimeter using the subplot grid and their estimated heights were recorded.

5.5 Results and Discussion

Data from the permanent monitoring plots now exist. These are intended for use in assessing vegetation change in the bog over time. Change can be determined by re-sampling these plots at 5-10 year intervals and comparing the percent cover values obtained with those from previous samples.

PART VI. RECOMMENDATIONS

To maintain the biological qualities that make Spruce Hole Bog a National Natural Landmark the bog should be managed so as to minimize two kinds of impact.

First, actions that would dramatically affect water levels in the bog should be avoided. Some variation in water level occurs naturally and, in fact, this data suggests a gradual rise in water table. However, if water level increased at a faster rate than peat accumulates, plant species associated with wetter areas of the bog will increase in abundance while species of the bog forest, such as black spruce, will decrease and perhaps even disappear. Lowering water levels would have the opposite effect, with likely invasion of the drier communities by certain tree species, including white pine and red maple.

Second, damage to the bog mat (the layer of peat in which living plants are rooted) should be minimized. Repeated trampling by humans can displace and compact the bog mat, reducing the area available for plants and other organisms that require a bog mat and making conditions more favorable for organisms that do well in open water. The bog should be checked occasionally for evidence of trampling. Should trampling become a problem, it may be worthwhile for the Town to consider some action. This might be as simple as requesting UNH faculty to reduce the number of class field trips taken to the bog, or as complex as constructing a small boardwalk over the bog mat, A boardwalk would allow visitors to view the salient features of the bog without damaging them. At present, we do not believe trampling is a serious problem at Spruce Hole.

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